**CASCADE: Computational Assessments of Scenarios of Change
for the Delta Ecosystem** [*]

"Scenarios are a tool for helping us to take a long view in a world of great uncertainty"
(Schwartz 1991)

1. Purpose

Agencies of the CALFED Bay-Delta Authority (CBDA) have accepted a challenge of California resource management that is unprecedented in scope and complexity. CBDA programs will invest many billions of taxpayer dollars over decades to attain multiple, often conflicting, goals of resource allocation. Decisions made within CBDA have enormous potential impacts on California's $30 billion agricultural industry, quality of life of its growing population, and sustainability of diverse communities of native species and their supporting ecosystem functions. While the cost and scope of CBDA programs are large, the outcomes of cumulative CBDA actions are highly uncertain. For this reason, CBDA has embraced the principle that its goals of stabilizing water supplies, providing safe drinking water and restoring ecosystems can best be attained with investments in science building toward a mechanistic understanding to guide design and anticipate the potential outcomes of costly actions. This proposal describes a research project conceived as a step toward a long view (Carpenter 2002) of CBDA actions. The urgency of a long view comes from the certainty that forces influencing water supply and water and habitat quality in the Sacramento-San Joaquin Rivers and Delta will change in the future.

A recent assessment, based on a conservative rate of CO_2 emissions and two independent global climate models, projects that California's statewide annual temperature will increase by more than 1ºC by the mid-21st century (Hayhoe et al. 2004). Projected thermal expansion of the oceans and melting of polar ice will raise sea level 9-13 cm, annual snowpack in the Sierra Nevada Mountains will decline by 26-40%, and April-June reservoir inflow will decline by 11-24% as a result of reduced snowfall and earlier snowmelt. The combination of earlier runoff and higher sea levels will increase the risk of flooding (Hayhoe et al. 2004) and levee failures in the Delta more catastrophic than the 2004 levee break that flooded Jones Tract (http://www.publicaffairs.water.ca.gov/newsreleases/2004/jones04.cfm). Water demand will increase and landscapes will continually evolve as California's population adds 15 million people during the 30-year time frame of the CALFED Ecosystem Restoration Program (http://calwater.ca.gov/Programs/EcosystemRestoration/Ecosystem.shtml). Trends of reduced sediment input to the Delta (Wright and Schoellhamer 2004) and erosion of San Francisco Bay (Jaffe et al. 1998) will continue. And the Delta landscape will be transformed by structural changes designed to create new habitats or hold or transfer water (http://www.delta.dfg.ca.gov/erpdeltaplan/). This proposal is motivated by the **question**: How will these changes alter the Delta-River-Watershed system and its capacity to provide safe drinking water and sustain both rich communities of native species and California's irrigation-based agriculture?

The **goals** of this project are to develop and apply a model-based approach of ecological forecasting (Clark 2001) to project future states of the Delta ecosystem under prescribed scenarios of change, and to communicate the outcomes of those scenarios to resource managers facing the daunting challenge of meeting CBDA goals in a continually changing world. The **objectives** of this project are to:

---

[*] This entire proposal, including supplemental materials not included in this document, is available at our web site: http://sfbay.wr.usgs.gov/access/CF_Scenarios.

- Develop/refine/calibrate/verify a set of mechanistic numerical models of climate, watershed hydrology, Bay-Delta hydrodynamics, sediments and geomorphology, and water quality
- Link these models to project system dynamics from prescribed forcings, beginning with the climate system (including sea level) and then cascading to the watershed (water, sediment, contaminant runoff), river system (flow, heat, sediment and contaminant transport), and Delta-Bay (hydrodynamics, water temperature, salinity, primary productivity, suspended sediments, geomorphology)
- Compare projections under prescribed scenarios of within-Delta habitat change and catastrophic levee failures
- Apply model projections to assess changes in water and habitat quality, potential habitat expansion of key alien species (*Egeria*, *Corbicula*, *Potamocorbula*), incorporation of contaminants such as mercury and selenium into foodwebs, and qualitative population responses of native fishes
- Work in collaboration with CBDA agencies and interested stakeholders to develop flexible strategic plans based on a range of plausible, quantitative depictions of the BDRW system as it changes during the 21st century

2. Description

Design of this study is built from **hypotheses** that: (1) California's hydrology will change during the 21st century in response to global warming; (2) water management and ecosystem structure and function will respond to changes in California's water supply, population, land use, sea level, constructed habitats and storage-conveyance facilities, and potential levee failures; (3) sufficient information is available to project plausible ranges of change in each of these forcings; (4) climatic, hydrologic, hydrodynamic, water-quality, geomorphic and ecosystem processes are linked in the Bay-Delta-River-Watershed system, and thus models to project future conditions there must also be linked; and (5) strategic planning by CBDA will benefit from mechanistic, ecosystem-scale projections of future forcings and responses, posed as plausible scenarios of system change.

The research project described here is based on a **conceptual model** ([Fig. 1](#)) built from the following principles:

- San Francisco Bay, the Sacramento-San Joaquin Delta, their tributary Rivers and Watersheds are one system of interconnected landscapes (we will refer to this as the **BDRW system**).
- The primary linkage medium between these landscapes is surface water including precipitation, runoff, streamflow, and effects of storage, conveyances, consumption, and estuary-ocean exchanges.
- These hydrologic processes are primary drivers of change in the chemical, sedimentological, and biological properties of the BDRW system (and therefore the outcomes of CBDA actions).
- BDRW hydrologic processes will change during the 21st century due to altered global-scale external forcings and regional-to-local scale internal forcings.
- External forcings will reach the BDRW from the atmosphere (as variable air temperature, solar radiation, winds, precipitation, pressure) and from the coastal ocean (regional currents, sea level, tides, temperature).
- Internal forcings include modifications of land use (associated with economic and population trends), structural alterations within the Delta (levee failures, new storage or conveyance facilities or constructed habitats), and altered water operations.

- The overarching conceptual model guiding this project is that: (a) hydrologic processes in the BDRW system will be altered by changes in both external and internal forcings; and (b) system-level effects will include a cascading set of interconnected changes in Bay-Delta hydrodynamics and transports, sediment supplies and geomorphology, habitat and water quality, and distributions and abundance of native and alien species. Each of these cause-effect relationships is relevant to CBDA's four general goals (Fig. 1).

We propose to modify and link numerical models of key processes (Fig. 2) to explore likely responses to plausible future changes in the external and internal forcings that drive BDRW ecosystem dynamics. The changes to be considered will take the form of three types of scenarios (described in more detail below), to be considered separately at first and then in combination:

- Climate Change
- Population and Land Use Change
- Delta Configurational Change

The cascading effects of changes under these scenarios will be followed as they propagate from the climate system to watersheds to river networks to the Delta and San Francisco Bay (Fig. 2). The resulting linked modeling system will provide a scenario evaluation capability that may be used subsequently to assess a variety of possible management approaches to accommodating the projected changes.

The approach links, hierarchically, seven project elements:

① Climate Modeling and Downscaling
② Sacramento-San Joaquin Watershed and San Francisco Bay Modeling
③ Delta Modeling: Hydrodynamics with Temperature and Phytoplankton
④ Sediment, Geomorphology and Tidal-Habitat Modeling
⑤ Fate and Effects of Selenium, Mercury, Silver and Cadmium
⑥ Invasive Species– *Potamocorbula*, *Corbicula*, and *Egeria*
⑦ Native and Alien Fish Population Trends

These elements are described in the remainder of this section. The flow of information between project elements is shown schematically in Figure 2. For example, outputs from the climate element① (air temperature, precipitation, insolation) are required inputs to drive the hydrologic model②. Outputs from the hydrologic model (e.g. river discharge) are required inputs to drive the Delta hydrodynamic model③, and so on. This figure maps the specific input-output linkages to guide readers as they follow signal propagation from one model to the next.

Climate Modeling and Downscaling ①
Investigators – Michael Dettinger, Daniel Cayan, Noah Knowles
Problem – General-circulation models (GCMs) of the global climate project that increasing concentrations of atmospheric greenhouse gases will result in a warmer California (Cubasch and Meehl 2001), with temperature increases ranging from about 2 to 5ºC by the end of the 21st Century (Fig. 3). Projections of future precipitation in California are much more scattered, with most models yielding relatively small precipitation increases or decreases (Fig. 3). These changes are projected in the midst of a general tendency for the hydrologic cycle to intensify, so wet episodes become wetter and dry episodes become drier with global warming. Moreover, paleoclimate reconstructions indicate that long and frequent droughts have been more common

in California in past centuries ([Fig. S-1](#))[*], so a return to drought-rich conditions is a plausible scenario of California's 21st century climate. Related to climate change is the potential for warming-related rise in sea level, projected to be 20 to 90 cm by the end of the 21st century (Church and Gregory 2001).

The likely responses of California's watersheds, rivers, and (some) ecosystems to projections of future temperatures and precipitation have been studied and simulated in previous studies (e.g. Gleick 1987; Jeton et al. 1996; Knowles and Cayan 2002, 2004; Dettinger et al. 2004). Earlier snowmelt and runoff, larger and more frequent winter floods, and much drier summertime soil and riverine conditions are projected under all plausible scenarios. A more complete assessment of the potential impacts of climate change on the BDRW system requires inclusion of responses by the high-altitude and low-altitude, managed and unmanaged parts of the watershed and estuarine system, and inclusion of sea-level projections that are consistent with the climatic changes. Realistic projections of 21st Century conditions require inclusion of other forces of change that will occur concurrently with climate change, including population growth and alterations of Delta plumbing. We will identify and characterize linkages from climatic change to meteorological, hydrological, and sea-level responses as the starting place for multidisciplinary assessment of the future BDRW ecosystem.

We will develop several detailed climate-change scenarios, two serving as bookends representing the outer reaches of up-to-date projections, and a third scenario reflecting a future climate with more frequent or sustained droughts and warming, motivated by paleoclimatic results that suggest that such droughts have occurred more than once in California's past:

- Climate Scenario 1: large warming and sea-level rise, fairly stable precipitation
- Climate Scenario 2: small warming and sea-level rise, fairly stable precipitation
- Climate Scenario 3: medium warming and sea-level rise, extended droughts

Tools/Analyses – GCMs simulate climate on coarse (200 km) spatial grids. As part of efforts at Scripps Institution of Oceanography funded by the California Energy Commission, we have been collecting and analyzing simulations of 21st Century climate over California by almost a dozen different GCMs (Dettinger in press). These ongoing efforts will inform our decisions as to the most robust choices of climate scenarios for the proposed study. The collection of simulations will provide the daily-to-monthly climate series that will be "downscaled" for use in this study. Downscaling is the process of interpolating large-scale climate projections down to the local scales (1-10 km) necessary for input to watershed and hydrologic models. Some previous studies have used high-resolution regional climate models nested within the output from a GCM (e.g., Leung et al. 2004). We have examples of such "dynamically downscaled" scenarios from previous studies by the PIs, but, at present, dynamically downscaled scenarios are restricted to snapshots of a decade or so of future climate (by their high computational expense) rather than the continuous 200-yr scenarios that are needed for the proposed study. Thus we will primarily use examples of dynamically downscaled climate-change scenarios to help validate more readily generated statistically downscaled scenarios. Statistical downscaling methods include weather-typing approaches (e.g., Dettinger and Cayan 1992), stochastic weather generators (e.g., Jeton et al. 1996), multiple-regression methods (e.g., Wilby and Dettinger

---

[*] Figures designated with an 'S-' prefix are included in the supplemental material available on our website http://sfbay.wr.usgs.gov/access/CF_Scenarios. Clicking on the figure links embedded in the text should open the corresponding figure directly in your pdf reader or web browser. Figures not designated with an 'S-' are included at the end of this document, and can also be accessed directly by clicking on their links.

2000), and deterministic mappings (e.g., Dettinger et al. 2004). Statistical methods are trained to adjust various GCM outputs to match selected statistics of real-world weather observations. In the present study, a new version of the downscaling method of Dettinger et al. (2004) will be the starting point; under the auspices of the California Energy Commission-funded studies mentioned earlier, other, more physically based statistical methods may be developed and used to provide the required downscaled scenarios. The drought scenario will be produced from the historical record as conditioned by paleoclimate reconstructions to achieve specific scenario designs (e.g., Tarboton 1995).

Required Inputs – Climate-change projections for the 21st Century are available as monthly series of surface-air temperatures and precipitation from about eight coupled ocean-atmosphere GCM models (e.g., from http://ipcc-ddc.cru.uea.ac.uk/dkrz/dkrz_index.html). At present, we propose to acquire daily outputs from the National Center for Atmospheric Research's PCM and the British Hadley Center's HadCM3 models which yield, respectively, some of the coolest and warmest climate projections. We will choose among current models to best represent the current range of projected warming rates; thus the specific choice of models may change as our understanding and analysis of available climate-change projections evolves (Dettinger, in press).

Outputs – will be downscaled climate scenarios in the form of daily weather series at 200 stations for the 20th and 21st Century, with concurrent and consistent sets of sea-temperature and sea level variability and trends. A large number of stations specifically chosen to meet the input needs of the other modeling elements described below will be included among the 200 sites; but other sites that may be of use to other aspects of the CALFED Science Program also may be included. Climate variables will include daily surface-air temperature and precipitation, solar insolation, surface humidity, and sea level rise near the mouth of San Francisco Bay. Weather time series for each climate scenario will be the starting place for assessing BDRW responses through the hierarchically linked models depicted in Fig. 2.

Along with the specific climate-change scenarios described earlier, the overall statistics of an ensemble of as many up-to-date projections as can be obtained of 21st Century climate in the Bay-Delta watershed will be derived by the methods of Dettinger (in press), so that the likelihoods of the particular scenarios provided to the other project elements can be determined and communicated. For example, we will determine what percentage of all projections lie "between" the warmer and cooler scenarios; we will determine what percentage of projections fall between the drier and "unchanged" precipitation scenarios. These measures of the likelihoods of the scenarios will provide a crucial context for the uncertainty characterizations in the rest of the study, a context that all recent "bookending" studies of climate-change impacts in California have lacked. Additional scenarios that reflect other parts of the distribution of available climate-change projections will be provided to project elements that can use them. The primary climate scenarios described above will also be provided, online, to other studies that want to parallel our efforts.

Sacramento-San Joaquin Watershed and San Francisco Bay Modeling ②a,b

Investigators – Noah Knowles, Daniel Cayan, Michael Dettinger, Dave Peterson (with consultation from Hugo Hidalgo, DWR Modeling Support Branch, and USBR Division of Planning)

Problem – Changes in climate, land use, and freshwater demand must be translated into downstream hydrologic changes in order to produce a meaningful assessment of their ecological impacts. This element will develop and apply modeling tools to assess responses of the watershed and estuary to the three climate-change scenarios described above, in addition to Delta configuration change and human population/land use change scenarios (described below). Watershed models will simulate responses of streamflow and temperature above and below

major reservoirs, and salinity of Delta inflows. An estuarine model will be used to assess responses of salinity and residual currents in San Francisco Bay.

Tools/Analyses –

❷a **Hydrologic Model**. At the core of this project element, the Bay-Delta Watershed Model (BDWM) is a physically based model of hydrologic processes that generate streamflow. It operates at a daily time step with primary inputs of precipitation and air temperature (Knowles 2000). The model simulates hydrologic variability in the entire Sacramento-San Joaquin watershed at a spatial resolution of 4 km. All model parameters are determined from fundamental physical considerations of soil properties, land cover, and topography, so BDWM requires minimal calibration and is uniquely well suited for studies of non-historical hydrologic scenarios as in this study. It is also computationally efficient, enabling the numerous simulations required to evaluate uncertainty (see below). The model simulates snow accumulation and ablation (using Tarboton and Luce 1996) and soil moisture fluxes, and contains a river routing component that integrates streamflow from throughout the watershed to determine total outflow. Figure 4 shows an example application of BDWM to assess potential hydrologic impacts from climate change projections through 2060.

An operations component will be coupled to BDWM, using DWR's CALSIM II (http://modeling.water.ca.gov/hydro/model/index.html). Changes in CALSIM hydrological inputs corresponding to the different scenarios will be derived from hydrologic simulations using the BDWM. These altered inputs will then be used by Dr. Hugo Hidalgo of Scripps Institution of Oceanography to drive CALSIM, and the results will be compared with outputs from a "base run" using unchanged inputs, providing an assessment of the role of management in translating upstream changes in hydrology, freshwater demand, and land use into downstream impacts, including changes in Delta inflows. The DWR Modeling support branch has agreed to provide additional assistance in validating and interpreting output from the CALSIM runs. The CALSIM simulations will also provide projections of the likely responses of Delta-inflow salinities to the scenarios evaluated. The USBR Division of Planning has agreed to apply their reservoir- and stream-temperature model RST to assess temperature changes under each scenario. The USBR model uses inputs of air temperature at selected stations, output from the CALSIM model, and monthly average reservoir inflow temperatures to compute monthly reservoir and stream temperatures at and below major reservoirs. Future reservoir inflow temperature variations will be estimated by developing statistical models of historical high-altitude stream-temperature responses to factors including air temperature and fractions of inflow composed of snowmelt and rainfall, and applying those models to the future climate projections.

❷b **SF Bay Model.** The BDWM has been linked to the UP estuarine model (Uncles and Peterson 1995), which calculates daily salinity and axial residual currents in San Francisco Bay and Delta. The UP model reproduces patterns of salinity variability at weekly to interannual time scales over a wide range of flow regimes (Knowles et al. 1997), and is computationally efficient enough to allow the numerous runs needed to evaluate ensembles of climatic scenarios, allowing evaluation of uncertainty. Figure S-2 shows the potential estuarine impact of the projected upstream 2060 hydrologic changes (Fig. 4). These results do not yet include effects of sea level rise, management adaptations, or potential Delta configurational changes, all of which will be included in the proposed scenario evaluations, providing a more complete assessment of the interactions of the various potential influences and their ultimate impact on the estuary.

Required Inputs – For each climate-change scenario, estimates of sea level, sea temperature, air temperature, specific humidity, insolation, and precipitation over the watershed will be provided as described in the climate element❶. The land-use/population change scenarios require forecasts of changes in the watershed including urbanization, farmland conversion, and changes in freshwater demand patterns due to population trends. This information will be obtained through DWR Modeling Support Branch for projected 2030 conditions (these data are

currently in preparation for Bulletin 160-04, the California Water Plan Update: http://www.waterplan.water.ca.gov/b160/indexb160.html). For scenarios where in-Delta effects on Delta outflow are deemed significant, output from Delta TRIM③ will drive the UP model; otherwise outflows from BDWM②a will drive UP directly.

Outputs – will be salinity and residual currents throughout the estuary, inflows from the watershed via the Sacramento, San Joaquin, and "east side" rivers, and flow rates, salinities, and temperatures in the rivers of the watershed. Flows, temperatures, and estuarine salinities will be simulated daily for the 20th and 21st centuries to provide representations not only of trending conditions, but also of plausible daily-interdecadal variations in the altered system. The hydrologic and estuarine models will provide altered salinity, inflows, and temperatures at the Delta boundaries for use in the Delta modeling element③. Projected changes in streamflow rates, temperatures, and salinity in the watershed will be used by the sediment-geomorphology④, contaminants⑤, invasive species⑥ and fish⑦ elements in addition to more detailed outputs produced by the Delta modeling element③.

In addition to the outputs corresponding to the specific scenarios described above, the ensembles of up-to-date climate projections described in the climate element① will be used to drive corresponding ensemble simulations of the BDWM, CALSIM II, and UP models. This will allow provision of ensemble outputs of Delta inflow and river and estuarine salinity, among other quantities, to those project elements that can use them. Further, these ensemble runs will allow characterization of the specific scenario outputs from these models in terms of the quantitative "bookending" probabilities described in the climate element①, allowing the estimates of uncertainty to be propagated more completely to other project elements.

Delta Modeling: Hydrodynamics with Temperature and Phytoplankton ③

Investigators – Nancy Monsen, Lisa Lucas, James Cloern, Postdoctoral position to be hired (with consultation from Mark Stacey)

Problem – The Delta is the central hub that links hydrologically driven variability in the watersheds and rivers to the estuary. It supplies drinking water to 23 million Californians, is habitat for native species, provides a conduit supplying water to the State Water Project (SWP) and Central Valley Project (CVP), sustains diverse agriculture in farmlands protected from inundation by vulnerable levees, and will be transformed by CBDA actions to build new habitats and water storage-conveyance facilities.

Climate-driven hydrologic change and sea level rise will potentially lead to profound changes in hydrodynamic processes within the Delta, including those controlling water transport, quality and temperature. In addition, anthropogenic changes, including new Delta structures, and catastrophic levee failure may also occur during the next 50 years and could significantly change transport through the Delta. We will apply a high-resolution hydrodynamic model (Delta TRIM) that runs in 2-D (depth-averaged) or 3-D mode to assess transport, water quality and temperature responses to the prescribed scenarios of climate change, population and land use change, and physical changes to the Delta. These scenarios will help assess the significance of changes in circulation due to climate and population change compared to those due to physical changes in the Delta.

Tools/Analyses –There will be three separate yet interconnected modeling components: a) Delta hydrodynamic modeling (stage, velocity, and scalar transport), b) temperature modeling, and c) phytoplankton dynamics (modeled as biomass and primary production). The core routines in Delta TRIM are the TRIM3D hydrodynamic model (Casulli and Cattani 1994) and the transport routines developed by Gross et al. (1999). Delta TRIM computes tidal-scale water motions using a fine scale (50 m) computation grid that resolves currents and stage in the small, interconnected channels characteristic of the Delta. Monsen (2001) incorporated Delta-specific

operations such as gate operations, pumping and agricultural diversions and returns into the TRIM3D model, and created the associated bathymetric grid. The model has been calibrated and verified (depth-averaged 2D mode) by comparing model results to measurements throughout Suisun Bay and the Delta for several time periods spanning a range of inflows and operational manipulations. An example application (Fig. S-3) shows spatial variability of source water in the interior Delta.

Dr. Mark Stacey (University of California Berkeley) and graduate students are currently developing a 3D temperature model (based on Rosati and Miyakoda 1988) coupled to TRIM3D for analysis of heating and cooling in Mildred Island, a sub-domain of the Delta. The temperature model is being calibrated against an extensive dataset collected from a current CALFED-funded study (Fig. S-4), but it has not been extended to the complete Delta domain.

We propose to also model trends in Delta phytoplankton biomass and production because previous studies have demonstrated that phytoplankton primary production is the most important source of organic matter fueling secondary production in the Delta (Jassby and Cloern 2000). Phytoplankton biomass is the dominant food supply to the Delta's planktonic food webs that produce forage for larval and juvenile fish (Sobczak et al. 2002). Delta-wide primary production is low compared to estuaries globally, and this damped food-supply function leads to food limitation of freshwater zooplankton such as cladocerans (Mueller-Solger et al. 2003). Delta-wide primary production has declined significantly in the past three decades (Jassby et al. 2002), and we will apply an existing model (TRIM-BIO) to project future changes under the set of scenarios prescribed above. TRIM-BIO is a depth-averaged hydrodynamic model (TRIM2D) with incorporated depth-averaged phytoplankton dynamics, developed by Lucas et al. (1999) to study interactions between hydrodynamic processes and phytoplankton dynamics in shallow estuaries (Fig. S-5). Modeling work under a current CALFED grant involves adapting the TRIM-BIO biological module for use with the TRIM3D hydrodynamic model for two sub-domains of the Delta (Franks Tract and Mildred Island). The biological module will calculate the time- and space-dependent photosynthesis, respiration and growth rate of phytoplankton, as well as consumption by zooplankton and benthic consumers, while they are transported through the Delta domain. Phytoplankton growth and losses to grazing will be modeled as by Lucas et al. (2002) and Lucas and Cloern (2002).

We have selected TRIM3D as the base Delta hydrodynamic model for a variety of reasons. First, the hydrodynamic code and transport routines appear extensively in the peer-reviewed literature. Gross et al. (1999) showed that the transport scheme conserves mass, a key attribute for biological models. Second, the model is multidimensional. This allows us to better represent exchange between the shallow water environments and the channels. Third, depth-dependent friction factors are used to calibrate TRIM3D. Because this tuning factor is globally valid, specific regions within the Delta TRIM domain do not have special tuning coefficients. Therefore, bathymetric changes to the system can be modeled without invalidating the model calibration. Fourth, Lucas has previously demonstrated the ability to couple phytoplankton and hydrodynamics with TRIM for a South Bay application (Lucas et al. 1999a, Lucas et al. 1999b). Fifth, the work of linking the temperature module with TRIM is already in progress.

The first phase of the Delta modeling effort will involve model enhancements required to address the climate change scenarios. 1) The bathymetric grid for the Delta TRIM model will be improved and the Sacramento River boundary relocated so the model can use flow input data from BDWM❷ and calculate transport through the Yolo Bypass. Once the bathymetry grid is modified to include the Yolo Bypass, the Delta TRIM model will be re-calibrated and verified both in 2D (depth-averaged) and 3D modes using existing datasets from several time periods spanning a range of inflows and operational manipulations. 2) The domain of the temperature module will be expanded from the current sub-domain around Mildred Island to include the proposed extended domain of Delta TRIM (Delta, Suisun Bay, and the Yolo Bypass). The

temperature module will be calibrated and verified both in 2D (depth-averaged) and 3D modes against water temperature measurements throughout the Delta using light attenuation as the tuning parameter. 3) The phytoplankton modeling will also be expanded to include the full Delta TRIM domain after the calibration and verification of the temperature module is completed. In the second phase of the Delta modeling effort, the models will be used as a tool to investigate both physical and climate changes to the system. Because Delta TRIM is highly resolved spatially, the model runs will be limited temporally to a 3-6 month period for each scenario. We will perform 3D simulations for two or three scenarios where we anticipate salinity intrusion or temperature stratification to be important (i.e. reduced summer inflows due to warming or the levee failure scenario). The other scenarios will be run in 2D depth-averaged mode.

Errors associated with the Delta modeling element of this project will be determined by comparing model output for historical cases with measurements for simulation periods that encompass both wet and dry seasons and a range of habitats (e.g. deep channels, shallower open water areas). Calculated velocity, stage, flow, salinity, temperature, and phytoplankton biomass from the base hydrodynamic model, temperature module, and biological module will be compared with local- and Delta-scale measurements. These data will include measurements from previous studies including current CALFED-funded measurements in the Mildred Island, Franks Tract, and Three Mile Slough. We will also use data from the USGS flow network and IEP'S Environmental Monitoring Program (stage, salinity and temperature stations throughout the Delta). Metrics to be used for quantifying the comparisons may include magnitude and phase errors derived from harmonic analysis for tidally influenced parameters (e.g. flow, stage) and bulk quantities such as net flow and tidally or spatially averaged salinity, temperature, and chlorophyll.

Required inputs and outputs are described in the following (*Figure S-6 contains a summary of all the required inputs for all the models, the sources of the data for each simulation*).

Base Delta TRIM hydrodynamic model
Inputs – Two scenarios of altered Delta bathymetric configuration will be compared to the baseline Delta physical configuration of 2003 using historical data to drive hydrologic boundary conditions. The first scenario of intentional channel transformation is based on structural changes described in the CBDA Conveyance Program Multi-Year Program Plan (Fig. 5). The second scenario of unintentional reconfiguration depicts catastrophic levee failure from a large earthquake, based on the CALFED Levee System Integrity Program Plan (Fig. 6). Delta TRIM is driven by boundary conditions of river inflow (provided either from historical data or BDWM②**a**), and tide stage at Martinez (provided either from historical data or the climate element①). Time-varying salinity at the upstream and downstream boundaries for the climate change scenarios will be provided by BDWM②**a** and UP②**b**, so this model will process inputs from three prescribed physical representations of the Delta and output from three models driven, ultimately, by GCMs (see Fig. 2).
Outputs – For each (3-6 month) simulation experiment, Delta TRIM will compute tidal and residual current speeds and directions, stage, salinity, source water mixture, and residence time across a 50-m grid over the full Delta domain. These outputs will provide projections of the future Delta under the scenarios described, including the following responses: timing and duration of Yolo Bypass inundations, salinity and source-water mixture at municipal intakes or export pumps, transport routes and rates throughout the Delta.

Temperature model
Inputs – Meteorological data (air temperature, wind speed, and solar radiation) determine the heat input to the temperature module. The Delta TRIM hydrodynamic model is used to

determine horizontal transport and vertical mixing (Mellor-Yamada 2.5 turbulence closure routine). For the physical change scenarios, observed temperatures at stations near each boundary and meteorological data from stations within the Delta will drive the model. GCMs① will provide the meteorological data. The USBR model②**a** will provide river boundary temperature data. GCMs, coupled with historical temperature profiles in SF Bay, will be used to develop statistical models to drive the western (bayside) temperature boundary condition.

Outputs – Temperature modeling will provide seasonal temperature distributions throughout the Delta. For the scenario runs in 3D, the percent of stratified area within the Delta will be calculated. Temperature distributions are key information for both the invasives⑥ and the fish⑦ elements of this proposal. Key questions to be addressed are: 1) How do shifts in timing and flow through the Yolo Bypass change the heat budget of the Delta, 2) What percent of the Delta is likely to stratify and for how long, and 3) What regions of the Delta will become warmer or cooler compared to the base case?

Phytoplankton model

Inputs – Effective phytoplankton growth is a function of water depth, water temperature, solar irradiance (PAR), light attenuation coefficients (derived from suspended sediment concentrations), nutrient concentrations, benthic grazing rates, and zooplankton grazing rates. As with the temperature model, Delta TRIM drives horizontal transport and vertical turbulent mixing of phytoplankton biomass. The water temperature will be calculated at each time step immediately before the phytoplankton subroutines. For the physical change scenarios, observed meteorological data will provide solar radiation, and light attenuation coefficients will be estimated from existing field data. For the climate change scenarios, GCMs① will provide meteorological data and the sediment transport element④ of this proposal will assist with estimation of light attenuation coefficients. Zooplankton grazing estimates will be based on the work of Lopez et al. (in review). Nutrients will be assumed replete for all scenarios, based on assessement of IEP monitoring data demonstrating that nutrients rarely limit algal growth in the Delta (Jassby et al. 2002). Boundary conditions for phytoplankton biomass transport into the system will be based on discrete and continuous chlorophyll *a* measurements by CDWR near the domain boundaries. We will examine historical chlorophyll *a* correlations with environmental variables (e.g. flow, temperature, and EC) to create a method to set boundary conditions for future scenarios.

Benthic grazing estimates will be based on an extensive survey of the benthos performed during a current CALFED-funded project, as modified by the invasive species element⑥ of this project. The phytoplankton-modeling element will provide a check on the phytoplankton biomass estimated within STELLA⑥ for developing benthic grazing rates.

Outputs – For scenarios resulting in extreme changes in transport rates (i.e. residence times), vertical density stratification, turbidity, grazing, or average water depth, we will calculate projected changes in the distribution and export of phytoplankton biomass. Phytoplankton primary productivity (PP) is the major metric by which we will compare various scenarios to the current Delta, thus questions we propose to answer include: 1) For a given scenario, does PP increase or decrease? 2) If PP increases, where (geographically, mechanistically) does the increase come from? 3) If PP decreases, what is the mechanism? Hydrodynamic flux, grazing, and growth rates will be quantitatively compared to generate a mass balance and answer these questions.

Sediment, Geomorphology and Tidal-Habitat Modeling ④

Investigators – David Schoellhamer, Bruce Jaffe, and Neil Ganju

Problem – Sediment transport and geomorphology are fundamental to the creation and

maintenance of tidal habitats. The prescribed scenarios will affect the evolution of San Francisco Bay-Delta tidal habitats. We will link separate models of Delta sedimentation, sediment supply to the estuarine subembayments, and subsequent ocean exchange, sediment redistribution, and geomorphic evolution within the estuary (Fig. 7). The models will be as simple as possible so that we can hindcast 130 years of bathymetry data, simulate 100 years into the future, and run numerous simulations to evaluate uncertainty, simulate stochastic hydrology, and evaluate multiple scenarios.

Tools/Analyses – We will construct and link models to compute: (1) Delta sedimentation–changes to the Delta sediment budget by Wright and Schoellhamer (submitted, Fig. S-7) will be estimated by estimating loads and distribution as a function of freshwater inflows. (2) Sediment supply to the subembayments of the estuary– this is the primary factor affecting geomorphic evolution and habitat creation (Fig S-8). A one-dimensional or modified Uncles-Peterson multi-box model (Lionberger 2003) will be used. (3) Sediment deposition and redistribution within subembayments of the estuary– the public-domain ROMS model (http://marine.rutgers.edu/po), which was used previously to model hydrodynamics and sediment transport in Suisun Bay (Warner et al., 2004) will be refined and tested for sediment supply and redistribution simulations, and long-term geomorphic evolution simulations. Presently, the refined model is being developed for Suisun Bay in collaboration with UC Davis through a University of California Water Resources Center Grant. A combination of the Delft 2DH (Roelvink et al. 2001) and 3D (Winterwerp 2001) coupled hydrodynamic, sand and mud transport models and morphology models within the Delft3D system (http://www.netcoast.nl/tools/rikz/delft3d.htm and http://www.wldelft.nl/soft/d3d/intro/) will be used in San Pablo Bay. Delft models are currently being used by Dan Hanes and Patrick Barnard, USGS, to model sediment exchange between the estuary and ocean. The knowledge gained from the ROMS and Delft models will be used to formulate a simplified model of geomorphic response to scenarios. Once the models are crosschecked and validated for benchmark cases, use of these two models optimizes existing collaborations and resources and improves confidence in the models by allowing comparison of results. (4) Future geomorphology of San Francisco Bay– the geomorphic model will compute tidal and wind wave redistribution of sediments and the subsequent evolution of shallow-water habitat, mudflats, and tidal wetlands (Fig. S-9). Geomorphic modeling techniques, including input filtering, empirical relations, and process-based modeling will be implemented and compared.

Required Inputs – For model calibration and validation, we will use the large database compiled by USGS and other agencies on bathymetry (Jaffe et al., in press; Jaffe et al. 1998; Capiella et al. 1999; Foxgrover et al. 2004), suspended-sediment concentration (Buchanan and Ganju 2004), and tributary inflow. Flow from the Delta and east side rivers will be provided by the watershed modeling element②**a**, in the varying scenarios created by the climate modeling team. Inputs to the Delta sedimentation model will be water discharge and a sediment rating curve developed by extrapolating data presented by Wright and Schoellhamer (2004). Inputs to the sediment delivery model will be water and sediment yield from the Delta sedimentation model, rate of sea-level rise from the GCMs①, and the Delta structural configurations prescribed above (in ③). Inputs to the geomorphic evolution model will be output from the sediment delivery model, sediment delivery from local tributaries (estimated by regression of historical sediment loads on flow rates), and sea level rise and wind climatology from the GCMs①. Historical Suisun Bay (Capiella et al. 1999) and San Pablo Bay (Jaffe et al., in press; Jaffe et al. 1998) bathymetric analyses of the past century will be used to test the Bay geomorphology model.

Outputs – We will estimate changes in Delta sedimentation for each climate change scenario. The sediment supply model will route sediment from the Delta to the subembayments of the estuary. The geomorphic evolution models will determine altered bathymetry in San Pablo and

Suisun Bays, which will be applied in the UP model②**b** to estimate resulting changes in salt transport into the Delta. In addition, geomorphic evolution models will simulate long-term changes in depth, and therefore habitat evolution within San Francisco Bay, which will be used by the invasives⑥ and fish⑦ studies in this proposal.

Fate and Effects of Selenium, Mercury, Silver and Cadmium ⑤

Investigator – Robin Stewart

Problem – Pollutant effects in San Francisco Bay are tied in complex and interactive ways to hydrology, hydrodynamics, sediment transport, ecological processes and food web structure (Fig. 8). Four metals have been shown specifically to have adverse effects: selenium has disrupted food webs in the Central Valley (Luoma and Presser 2000); health advisories constrain human consumption of Bay-Delta fish because of mercury contamination and both silver and cadmium have historically impaired invertebrate growth in South San Francisco Bay (Hornberger *et al.* 2000; Brown *et al.* 2003). These metals have distinct origins and delivery pathways: Se from the San Joaquin Valley and refineries, Hg from the Sacramento River, Cd from mining in the Shasta district (Cain *et al.* 2000), Ag from local watersheds. The concentrations of these toxicants in the Delta and Bay vary with loadings from the source, amount of runoff, changes in sediment load, chemistry of the runoff, and the source of runoff. The effects of the contaminants are determined by their concentration, chemistry and bioavailability in the Bay or Delta. The goal here is to contrast how future hydrologic scenarios might alter concentrations of the contaminants, and the implications of those changes for bioavailability and potential adverse effects.

Tools/Analyses – We will extend to the four contaminants the approach used to compute selenium effects in San Francisco Bay for varying scenarios of altered loadings, developed by Luoma and Presser (2000). The approach establishes metal loadings scenarios from source-specific information. Inflows to the Bay (including source and chemistry) are used to determine concentrations. Partitioning coefficients and speciation are used to differentiate particulate and dissolved concentrations; a dynamic bioaccumulation model (DYMBAM, Schlekat *et al.* 2001) calculates uptake by the first trophic level; then empirically derived trophic-partitioning constants are used to calculate trophic transfer through the foodweb. For example, Luoma and Presser (2000) used this approach to propagate Se transfer through a bivalve-based food web to compute bioaccumulation in sturgeon and scaup (Fig. S-10). The approach will be applied to assess bioaccumulation, trophic transfer, and potential effects of four metals on predators⑦ from different food webs: invasive predators that feed from the water column (e.g. striped bass for mercury and selenium) and native predators (e.g. Sacramento splittail and/or sturgeon, which feed on bivalves⑥).

Required Inputs – Loading data for mercury and cadmium are available from the existing literature, and will be assembled for this study. Model bioaccumulation coefficients for mercury and cadmium are being developed for invertebrate species and for fish (Croteau, in preparation; Fisher, N. SUNY, CALFED ERP-02 P40). For silver, coefficients for uptake by invertebrates are available and those will be used for model projections. No food web analyses will be conducted for silver, because most effects appear to occur on lower trophic levels. Input from other project elements will be used to define different scenarios of source loading and/or runoff influences. For example, if inflows from the SJR increase relative to Sacramento R. inflows (from ②**a**), Se loads to and concentrations in the Bay-Delta will increase. The timing of such increases is crucial to determine Se exposures of migratory predators (information from fish element⑦). Similarly, if Sacramento R. inflows increase relative to the SJR, mercury and cadmium loads and concentrations could increase. If the timing of river flow changes, this will affect dilution of silver from internal sources, perhaps influencing the potential to affect reproduction in

invertebrates (timing of reproduction determined by the biological elements of the project⑥,⑦).

Outputs – For each scenario, we will compare projected monthly inflows, sources, sediment loads and either metal loadings or metal concentrations using flow outputs from BDWM② and transports computed by Delta TRIM③. The bioavailability/effects model will then be used to constrain influences of these changes on upper trophic level animals. The output will be a comparison, under different Delta scenarios, of potential stresses to selected invasive and native predators from different food webs. This stress can be one of the considerations in determining the suitability of ecological conditions in both the fish⑦ and invertebrate⑥ elements of the project.

Invasive Species– *Potamocorbula*, *Corbicula*, and *Egeria* ⑥

Investigator – Janet Thompson

Problem – One of the ERP goals is to "reduce the negative impacts of invasive species". We will look at three species that have displayed significant ecosystem effects and that have been sufficiently studied to allow us to project their distribution in response to the scenarios described in this proposal. Two of these species, the filter-feeding bivalves *Potamocorbula amurensis* (*PA*) and *Corbicula fluminea* (*CF*), have previously been shown to change the food web by controlling the biomass of phytoplankton at the base of the food web (Fig. S-11, Alpine and Cloern 1992, Lucas et al. 2002). These alien bivalves have the potential to impede progress of CALFED's ERP by consuming zooplankton, outcompeting native zooplankton, shrimp, and larval fish for food (Kimmerer 2002), and increasing the trophic transfer of contaminants (Stewart et al. 2004, Linville et al. 2002). The third exotic species, *Egeria densa* (*ED*), is a perennial freshwater submerged macrophyte that occupies about 8% of the surface area of the Delta and has transformed the shallow water habitat in the Delta to one that is now dominated by a denser (leaves and plants), more widely distributed, less seasonally variable, and more shade-tolerant species than was there before. As summarized by Brown (2003), the fish community in *ED* tends to be dominated by alien species and the edge of the *ED* beds dominated by alien piscivorous fish, so the few natives that appear to benefit from the food and refuge available in the *ED* are potentially more likely to be preyed upon. Areas such as Suisun Marsh, which presently has no beds of *ED,* may be prime restoration areas (Brown 2003) and it is important that we be able to understand conditions which may encourage *ED's* spread. Thus, we will assess potential changes in the distribution, biomass, and food consumption of *PA* and *CF*, and in the distribution and relative density of *ED*, for each scenario.

Tools/Analyses – We will construct several statistical models (e.g., GAM, logistic regression and CART) of the three species to estimate their potential distribution in the Bay and Delta for each scenario based on their known physiological tolerances and field distribution data (Fig. 9). Validity of all models will be determined by comparison to the following field data: (1) *Potamocorbula's* population structure and distribution since 1986 (Thompson 2004 and unpublished data); (2) *Corbicula's* present distribution (Fig. S-12, Parchaso and Thompson 2004), growth rates (USGS unpublished data, Foe and Knight 1985), and its population structure and recruitment history as reported by the CA Dept. of Water Resources Environmental Monitoring Program since 1977; and (3) *Egeria* distribution as reported by the CA Dept. of Boating and Waterways (2001) and the *Egeria* Project at the Romberg Tiburon Center (http://romberg.sfsu.edu/~egeria/). In addition, we will estimate biomass distribution for specified habitats in the Bay/Delta for CF and PA using a relatively inexpensive, "off the shelf" modeling program, STELLA (Ruth and Lindholm 2002). Both of these species dominate the community when they are present, recover quickly from disturbance, and interspecific competition does not appear to be a limiting factor for either species (Nichols et al. 1990, Thompson 2004, McMahon 1999). Thus we believe there is potential for successful multi-

dimensional landscape models of these species that dynamically link to hydrographic and phytoplankton models at some time in the future. We expect the STELLA models to give us order-of-magnitude estimates of biomass (and thus of grazing rate), and to highlight the life history parameters most in need of study before larger modeling efforts are attempted. Data will be reported by habitat type which will be defined by the environmental factors determined to limit the distribution of each species, based on the statistical modeling effort.

Two types of errors will be reported for predicted distributions based on statistical tools. The first type of error, that associated with the statistical method, is easiest to calculate. The second type of error is that in which the presence of an organism is predicted at a location where they are not present, or conversely, due to some unmeasured environmental factor. This type of error is more difficult to assess. Therefore we will establish that the predictions are potential distributions within the statistical error limits. Errors associated with rate parameters (e.g., growth), environmental variables (e.g. temperature), and model numerics (reviewed in Ruth and Lindholm 2002) will be assessed by running STELLA in Monte Carlo fashion with random sampling from parameter and input variable distributions. Overall error will be determined by sampling from all input and parameter distributions simultaneously, and the sensitivity of the species density and biomass to the model parameters will be established by applying this error propagation approach to each parameter separately. This sensitivity analysis will increase our understanding of the species and also help establish which errors are most important in our predictions. We will use this knowledge to reduce the error where possible, or at a minimum know which parameters are most important in our error propagation analyses. Model results for present-day conditions will be compared against known distributions and biomass values for the species during wet, dry and average hydrologic years to demonstrate the ramifications of these errors.

Required Inputs – Distribution models will require future scenarios values for seasonal streamflow, water temperature and salinity, phytoplankton biomass, current velocity, flood frequency, turbidity, and habitat evolution produced from the modeling elements described above (②**a,b**, ③, and ④). STELLA will require some of these same environmental variables in addition to biological estimates of rate of cohort (age)-specific growth and mortality, fecundity, recruitment, immigration, and emigration at a minimum. The Bay/Delta is in the mid-latitudinal range for both of these exotic bivalves and preliminary work by the USGS and others has shown that growth rate, reproductive rate, fecundity, and recruitment are most closely related to food and temperature in this system. Therefore these rates will be estimated through a combination of published rates and analysis of local field data (Fig. 9). Phytoplankton biomass will thus be required to run STELLA. Unfortunately, neither the time step or the sophistication of the population models can match with those of the TRIM ③ phytoplankton module at this time, and we will need to develop a submodel to estimate phytoplankton biomass assuming a local balance between phytoplankton growth rate and bivalve grazing rate (phytoplankton biomass will change as function of ③ and ④ model-derived values of temperature and turbidity, and published estimates of zooplankton grazing and irradiance). Phytoplankton biomass in this simple model will be reduced by a parameter derived from phytoplankton growth rate (from TRIM③) and clam grazing rate during each month, if needed (e.g., if depth-normalized grazing rate is twice the growth rate of phytoplankton, the biomass level will be reduced by half as a first estimate). Seasonal phytoplankton biomass will be compared to that predicted by TRIM (using the newly derived benthic grazing rates) and will be adjusted if needed. If necessary, we will iteratively run the STELLA models with TRIM to insure the correct benthic grazing rate is being applied for the appropriate phytoplankton biomass levels in TRIM. Initial conditions in the model will assume population structure and species distributions that are consistent with what we find today. A short "conditioning" period will be used to stabilize the phytoplankton submodel and clam growth model at the beginning of the model runs.

Outputs – will include, for each scenario: (1) Seasonal estimates of the distribution for *Egeria*, *Corbicula and Potamocorbula* based on habitat type, throughout Suisun Bay and the Delta; (2) Spatial distribution of the seasonal biomass levels and grazing rates for *Corbicula* and *Potamocorbula* based on habitat type; monthly data will be available as required for critical periods in the TRIM phytoplankton module and contaminant metals models. Grazing rates will be estimated as described in Lucas et al. (2002) and Thompson (2004).

Native and Alien Fish Population Trends ⑦
   Investigator – Larry R. Brown
   Problem – Restoration of native fish populations is a significant goal of CALFED's Ecosystem Restoration Program (ERP). Various management strategies are presently being considered or implemented to accomplish such restoration; however, it is unclear if the benefits of such strategies would be maintained in response to the hydrologic and physical changes in ecosystems that could occur in response to changes in climate, water use, and physical configuration. Fish species of the BDRW system are affected by many environmental factors (Bennett and Moyle 1996), including those responsive to climatic-hydrologic change (Fig. 1): salinity distribution as indexed by "X2" (Jassby et al. 1995, Kimmerer 2002); timing and duration of floodplain inundation (Sommer et al. 2001); flow and temperature as they affect spawning and growth (Feyrer and Healey 2003); the balance between native and alien fishes (Brown and Ford 2002); habitat quality as influenced by the distribution of *Egeria densa* (Brown 2003); stream temperature as it affects anadromous salmonids during upstream migration, spawning, and rearing (Moyle 2002); and high flow events that mobilize streambeds resulting in the loss of incubating eggs, or move larvae into unsuitable areas. The objective of this element is to determine if populations of selected native and alien fish species are likely to increase, decrease, or remain constant in response to environmental changes expected based on the scenarios defined above.
   Tools/Analyses – This project element will include two tasks. The first task will be to maintain communication with fisheries resource managers. Communication is needed so that the project team can remain informed about the critical information needs of managers, managers can remain informed about the progress of other project elements, and managers can remain informed about the degree to which the project team will be able to meet their needs. The PI will convene a committee of agency and academic scientists to fulfill this task. The group will meet face-to-face at least once a year with additional communications by e-mail and other methods as warranted.
   The second task will be to assess potential population responses through integration of quantitative depictions of future environments with species-specific ecophysiological and life-history information for target species. Assessments will comprise a series of subtasks:
   • Construct a qualitative life-history model (e.g., Fig. 10) based on existing information for each species of interest. For some species, models already exist (e.g., striped bass, splittail, anadromous salmonids). For others, models will have to be constructed from the literature and local information. The models will identify the periods in the life cycle when each species would be most vulnerable to changes in temperature, salinity, flow, and habitat changes.
   • Assess the likely population effects of the scenarios by comparing outputs of salinity and temperature distributions with salinity and temperature preferences/tolerances of native and alien fishes.
   • Assess the likely population effects of the scenarios by comparing outputs of flow patterns with available information on the responses of native and alien fishes to flow regime.
   • Assess the likely population effects of the scenarios regarding the fate and effects of selenium, mercury, silver and cadmium for the species modeled.

15

• Assess the likely population effects of changes in the distribution and density of *Egeria densa* to the extent possible given values and confidence in predicted salinity field, water temperatures and bathymetry from the Delta models.

• Predict overall responses (positive, negative, neutral) of fish populations to changes in temperature, salinity, flow, and habitat predicted by the scenarios.

• Summarize the predictions for the individual species into an integrated prediction for the fish community as a whole.

It is likely that sufficient information is available to construct life-history models for most of the common native and alien species. Evaluations of individual species responses will likely progress from professional judgment and simple conceptual models to predictions from simple qualitative models, such as loop analysis (Puccia and Levins 1985). The qualitative approach is necessary because actual population sizes of most fish species in the Delta are unknown, making quantitative evaluations impossible.

Required Inputs – For Task 2, assessments of population responses will begin with outputs from GCMs①, BDWM②**a**, Delta TRIM③, UP②**b**, and the geomorphic models④ as future scenarios of air and water temperature, seasonal streamflow and salinity distributions, Bay-Delta circulation patterns, flood frequency and floodplain inundation, and habitat mosaics. Assessments of the effects of changes in contaminants will be limited to the species modeled by Stewart⑤. Presently, such models are planned for striped bass, Sacramento splittail, and white sturgeon. Assessments of the distribution and relative density of the alien macrophyte *Egeria densa*⑥ will also be incorporated to the extent possible. Salinity, temperature and habitat preferences/tolerances of native and alien fishes will be determined from the literature. Responses of various species to changes in flow regime, such as severity and frequency of flood events and inundation of floodplain will also be assessed from the literature. Data collected by the Interagency Ecological Program and other local programs will be evaluated including fall mid-water trawl, summer townet, 20-mm survey, and Delta resident shoreline fish monitoring. Sufficient literature or local information must be available to construct a life-cycle model for each species to be assessed. Existing, locally derived life-cycle models will be utilized if available.

Outputs – Task 1 will inform all the project elements about the information needs of managers. Outputs of Task 2 will include: (1) a simple life-cycle model for each alien and native species considered; (2) an assessment of the likely population effects for those species of changes in temperature, salinity, habitat, and flow regime; and (3) an integrated community assessment of such changes representing visions of trends of fish community responses to a range of future conditions in the BDRW system.

3. Justification

Relevance to CBDA. Our goal is to link a multidisciplinary suite of analyses and models of the Bay-Delta-River-Watershed system to assess the likely outcomes from a set of scenarios. This effort will provide the basis for a new framework to help resource managers anticipate and plan for changes in California's water and ecosystem resources, in keeping with the programmatic objectives of the CALFED Bay-Delta Authority. Scenarios are used by innovative businesses to provide "*a context for thinking clearly about the impossibly complex array of factors that affect any decision*" and "*to make strategic decisions that will be sound for all plausible futures*" (Schwartz 1991). Clear thinking and sound decisions are going to be needed as the CALFED Ecosystem Restoration Program (ERP) implements the 300 targets and 600 programmatic actions envisioned in its Strategic Plan.

The urgency of developing a long view for CBDA planning was prominent in plenary

talks given by leading scientists at the 2004 CALFED Science Conference:

- "*Substantial increases in levee instability and associated failures will occur over the next 50 years, and thresholds may be crossed that lead to widespread multiple-island flooding events. All other CALFED/CBDA programs, specifically water supply reliability, drinking water quality and ecosystem restoration, will be significantly and negatively impacted by these events.*" (Jeffrey Mount).
- "[The long-term future of California's native fishes] *is cloudy given the certainty of long-term drought, climate change, sea-level rise, collapse of levee systems (especially in the Delta), new invasive species, and increasing human populations… If we do not plan for the major changes in California's aquatic ecosystems that are likely within the next 25-50 years, we will need expensive and temporary emergency measures to fix things following each successive disaster.*" (Peter Moyle).
- "*To meet our goals of restoring ecosystem function and preserving species in California aquatic systems, while continuing to supply our present and future water needs, requires that we … understand the functioning of present complex systems and simulate future response to climate and landscape/resource change.*" (Johnnie Moore, CALFED Lead Scientist).

This proposal describes a model-based approach for placing quantitative bounds on water resource and ecosystem responses to a plausible range of future changes in the BDRW system – critical information that will allow resource agencies to anticipate changes and develop flexibility in their strategic planning to accommodate those changes before they occur.

While this project has broad relevance to many goals of the CALFED Science Program, it is most directly relevant to the third priority research topic identified in the current PSP, which solicits "**analytical frameworks that will support assessments and refined predictions of how likely future changes such as population or climate-related hydrological shifts may affect water operations, ecosystem processes, and CALFED projects**".

The first product of this project will be a new approach linking climatic, hydrologic, hydrodynamic, biogeochemical, sediment/geomorphic, and biological models in a hierarchical manner to follow propagation of a prescribed signal (e.g. climate warming, levee failures) through cascading responses from the watershed, through the river system, and into the Delta and San Francisco Bay (Figs. 1 and 2). The coupling of models describing processes at different spatial scales (from global climate to Delta channels) provides an approach for viewing and exploring dynamics of the full system comprising the Delta, its watersheds, rivers, estuary, and coastal ocean. This approach will consolidate decades' worth of research findings from the project team's studies and data collection throughout the study area into a new and powerful capability for scenario evaluation to assist in strategic planning. The approach will provide a systems perspective for probing and understanding the interconnected components of the BDRW system. Modeling tools providing this perspective are essential for implementing ecosystem-based management, a guiding principle of the ERP: *"The Strategic Plan signals a fundamental shift in the way the ecological resources of the Bay-Delta ecosystem will be managed, because it embodies an ecosystem-based management approach with its attendant emphasis upon adaptive management. Traditional management of ecological resources has usually focused upon the needs of individual species. Ecosystem-based management, however, is a more integrated, systems approach that attempts to recover and protect multiple species by restoring or mimicking the natural physical processes that help create and maintain diverse and healthy habitats.*" The models to be refined and linked in this project were selected to describe those processes that are key drivers of change in habitat and water quality and capacity of the BDRW system to sustain diverse native communities and ecosystem functions.

In addition to providing an analytical/modeling framework to assess likely implications of future changes, these tools will be applied to "**consider the effects of different combinations of changes… on Delta habitats and ecological processes**". Accordingly, the second product will be model-based projections describing how the Delta ecosystem might respond to the combined effects of climate and anthropogenic change. The projections will include consideration of the complex, nonlinear, and often surprising consequences of interconnected processes. They will be valuable for planning as quantitative depictions of how the Delta system might evolve over time, and because the contrast and comparison of multiple scenarios provides one measure of the likely range of plausible future outcomes.

The ERP Strategic Plan is built around the approach of adaptive management: "*Restoring and managing the Bay-Delta ecosystem requires a flexible management framework that can generate, incorporate, and respond to new information and changing Bay-Delta conditions. Adaptive management provides such flexibility and opportunities for enhancing our understanding of the ecosystem…*". A potentially valuable mode of adaptive management is to simulate long-term experiments with numerical models so that resource managers can anticipate and formulate adaptations to the changes hypothesized above. NOAA's assessment of climate-change effects on U.S. coastal ecosystems further highlights the relevance of our proposal: "*Regional scenarios of climate change are critical in understanding how local ecosystems will be affected, and might ultimately respond, to global change…. such knowledge will provide a foundation for resource managers and the public in developing adaptation strategies*" (Boesch et al. 2000). Our goal is a set of well-analyzed scenarios for those agencies tasked with restoring ecosystem functions, creating new habitats, and recovering populations in the Bay-Delta-River-Watershed.

A variety of priority study topics are identified in the current proposal solicitation. In addition to the study topics related to modeling frameworks for future change assessments, the outcomes of this interdisciplinary research project are relevant to several of the Science Program's other priority study topics:

• **Environmental Influences on Key Species and Ecosystems** – we will assess implications of habitat change (geomorphology, temperature, salinity, contaminants) for both key alien species and key native species of fishes in the Delta including salmonids and Delta smelt.

• **Relative Stresses on Key Fish Species:** We will assess potential changes in 1) *food* by evaluating changes in the system primary production and colonization by the alien bivalves that have outcompeted native zooplankton for the phytoplankton food resource; 2) *contaminants* with assessments of potential trends in the threats of mercury, selenium, silver and cadmium to both human health and living resources in the Delta and Bay; and 3) *habitat* by assessing change in the evolution of restored habitats with analysis of Bay-Delta sediment budgets and geomorphology, colonization by *Egeria* and alien bivalves, and seasonal patterns of river flow, water temperature and salinity distributions as key habitat attributes for species of concern.

• **Processes Controlling Delta Water Quality** – with model-based projections of salinity intrusion into the Delta under prescribed scenarios of river flow, sea level, levee failure and structural changes within the Delta.

Feasibility. The proposed study is ambitious but feasible because it is a natural extension of research performed by the project team over the past 5-25 years. It was designed to integrate results from recent studies conducted by the PI team, including CALFED-supported studies that have strengthened the scientific foundation of the ERP Strategic Plan. This prior work has contributed new knowledge and data on: hydroclimatology; energy supplies to Delta foodwebs; transports, transformations, and trophic transfer of contaminants; regional and local patterns of water circulation and mixing in the Delta; primary and secondary productivity; processes through

which invasive species disrupt ecosystem functions; and sedimentation in the Delta and Suisun and San Pablo Bays. Many of the conceptual and numerical models described in this proposal were developed in previous CALFED (and USGS) projects of integrated ecosystem science. Our objective here is to integrate these efforts, producing new knowledge and a scenario evaluation capability to assist in the long-range planning of CBDA agencies.

The experiments that make up this project will link process models and observations that span major elements of the BDRW system. Many key models and supporting data already exist, although the "models" range from numerical models to simplified conceptual descriptions of key processes. Key challenges will be to mesh the disparate spatial and temporal scales characterizing the various model inputs and outputs.

The project has been designed with realistic goals, specifically limiting the study's scope to a small, tractable number of scenarios that can be precisely articulated. The goal is to combine existing knowledge with a set of models to accurately assess ecosystem responses to several plausible scenarios of change in climate, sea level, within-Delta structures, and land use and population. Given the limits of current knowledge and the innovative nature of the modeling linkages required for thorough analyses of even a few scenarios, we are not promising to produce a turnkey modeling system. Rather, we will lay the groundwork for a future, more generalized modeling framework while addressing some key scenarios specified to meet pressing needs of the CBDA Science Program. A key part of our strategy, that ensures feasibility of the study, is that we have carefully chosen a wide-ranging study team with deep roots in the CBDA region, and focus on those system attributes that are within our individual areas of scientific expertise.

Furthermore, this project is not designed to anticipate change in water supply reliability and management adaptations to that change: this challenge is met by the Department of Water Resources through its evolving State Water Plan. Our project is designed as a complement to the State Water Plan, considering ecosystem-scale consequences of future change. Eventually, assessments and tools of even broader scope than we propose will be needed as California's climate and landscapes continue to change. The scope of our future efforts will grow as products are made available to scientists having other areas of expertise, but the proposed study will set a high standard for these future studies and modeling tools and will provide a firm basis for such additions. We are comfortable with the self-imposed limitations in project scope because we recognize this effort as an initial step, preparing for more comprehensive assessments of the future than can be developed in three years. Finally, this project is feasible because it combines resources supported by CALFED and the USGS. The total project cost is $3.48M, of which $1.64M will be provided by USGS through its Priority Ecosystems Program that has supported studies by this PI team over the past decade.

Dissemination of Results. Members of the study team have actively produced management-relevant research in the Bay-Delta system for the past several decades. From this experience, we know that the most relevant science comes when potential customers are involved at project inception. Planning for this project began with a workshop (the agenda from this workshop is available HERE) to solicit guidance about study design from the public and panelists. The assembled panel represented the U.S. Bureau of Reclamation, California Department of Water Resources, California Department of Fish and Game, Nature Conservancy, Metropolitan Water District, and Contra Costa Water District. In the audience were members of the U.S. EPA, California Department of Water Resources, State Water Resources Control Board, California Department of Fish of Game, USBR, NOAA Fisheries, California Department of Boating and Waterways, California Energy Commission, and the California Legislature, among others. The strongest message we heard from the ~100 attendees was concern that this is a USGS-only project seemingly disconnected from resource managers. In response to that criticism, the PIs have designed their studies as collaborations with resource agencies or academic scientists.

Letters of commitment/support are included (available HERE) from the U.S. Environmental Protection Agency, U.S. Bureau of Reclamation, California Department of Water Resources, U.S. Forest Service, San Francisco Estuary Institute, and faculty at University of California Davis, Berkeley, and San Diego. The breadth of this support reflects a tradition of USGS scientists working in partnership with Bay-Delta management and regulatory agencies and the academic community. This tradition reflects our conviction that scientific advancements have little value until they affect environmental policy. We are committed to working with the CALFED Science Program and Ecosystem Restoration Program to establish a mechanism for continuing dialogue, such as annual meetings with agency staffs, to present progress reports and receive feedback.

The study team will continue its well-documented tradition of presenting new results in the IEP Newsletter, San Francisco Estuary Project's *Estuary*, USGS Fact Sheets, *San Francisco Estuary and Watershed Science* and syntheses as CALFED-solicited white papers. We will present results at CALFED Science Conferences, State of the Estuary Conferences, IEP Annual Meetings, as briefings before CBDA science boards and the BDAC. We will continue to serve, when called, as members of advisory panels and working groups convened by CBDA and its agencies.

The study team has been publishing the website *Access USGS ─ San Francisco Bay and Delta* (http://sfbay.wr.usgs.gov/) since the mid-1990s, a site that now receives more than 70,000 visits per month. This site has been an invaluable resource for parties needing immediate access to data and research products from our ongoing scientific efforts in the Bay and Delta. We will continue our long reliance on the *Access USGS* site to provide, to public and technical audiences, information on modeling tools and results; the quantitative projections of climate, streamflows, population/land use changes, etc. that specify the scenarios; maps and animations (e.g., snow coverage, salinity intrusion, geomorphic change); posters; and quarterly progress reports. Other intermediate products, such as inputs for sediment and biological models, will be posted with metadata. Our existing bibliographic database will be updated annually and USGS reports and journal articles will be posted in PDF format. We will continue our dedication to making new scientific information easily accessible and understandable for a broad audience.

Work Schedule. Team members have planned to begin this project in January 2006 and complete it in December 2008. Timelines for the sequence of tasks of each element are shown in Figure 11.

Supplemental Information. Further information, including supporting figures, letters of support, and the agenda from the public planning workshop are available online: http://sfbay.wr.usgs.gov/access/CF_Scenarios/

4. Literature Cited

Alpine, A.E., Cloern J.E., 1992. Trophic interactions and direct physical effects control phytoplankton biomass and production in an estuary. *Limnol Oceanogr* **37**: 946-955

Barko, J.W., and Smart, R.M. 1981. Comparative influences of light and temperature on the growth and metabolism of selected submersed freshwater macrophytes. *Ecol. Mono.* **51**:219-235.

Bennett W.A. and Moyle P.B. 1996. Where have all the fishes gone? Interactive factors producing fish declines in the Sacramento-San Joaquin estuary. In: Hollibaugh J.T., editor. San Francisco Bay: the ecosystem. San Francisco: Pacific Division of the American Association for the Advancement of Science. p 519-542.

Boesch, D.F., J.C. Field and D. Scavia (eds.). 2000. The Potential Consequences of Climate Variability and Change on Coastal Areas and Marine Resources. NOAA Coastal Ocean Program Decision Analysis Series No. 21. Silver Spring, MD. 163 pp.

Brown, L.R. and T.J. Ford. 2002. Effects of flow on the fish communities of a regulated California river: implications for managing native fishes. *River Research and Applications* **18**:331-342.

Brown, L.R., 2003. Will Tidal Wetland Restoration Enhance Populations of Native Fishes? In: Larry R. Brown, editor. Issues in San Francisco Estuary Tidal Wetlands Restoration. *San Francisco Estuary and Watershed Science*. Vol. **1**, Issue **1** (October 2003), Article 2. LINK.

Brown, C.L., Parchaso, F., Thompson, J.K., and Luoma, S.N. 2003. Assessing Toxicant Effects in a Complex Estuary: A Case Study of Effects of Silver on Reproduction in the Bivalve, *Potamocorbula amurensis*, in San Francisco Bay. *Human and Ecological Risk Assessment* **9**: 95-119.

Buchanan, P.A., and Ganju, N.K., 2004. Summary of suspended-sediment concentration data, San Francisco Bay, California, Water Year 2002: USGS OFR 2004-1219. LINK.

Cain, D. J., Carter, J. L., Fend, S. V., Luoma, S.N., Alpers, C.N., and Taylor, H. E. 2000.Metal exposure to a benthic macroinvertebrate, *Hydropsyche californica*, related to mine drainage in the Sacramento River. *Can. J. Fish. Aquat. Sci.* **57**:380-390.

California Department of boating and Waterways. 2001. Environmental Impact Report for the *Egeria densa* Control Program.

Cappiella, K., Malzone, C., Smith, R., and Jaffe, B., 1999. Sedimentation and Bathymetry Changes in Suisun Bay: 1867-1990: U.S. Geological Survey Open File Report 99-563.

Carpenter, S.R. 2002. Ecological futures: building an ecology of the long now. *Ecology* **83**: 2069-2083

Casulli, V. and E. Cattani. 1994. Stability, accuracy and efficiency of a semi-implicit method for three-dimensional shallow water flow. Computers *and Mathematics with Applications* **27(4)**: 99-112.

Chambers, P.A., Prepas, E.E., Hamilton, H.R., and Bothwell, M.L. 1991. Current velocity and its effect on aquatic macrophytes in flowing waters. *Ecol. Appl.* **1**:249-257

Church, J.A., and Gregory, J.M., 2001, Changes in sea level, in Houghton and others (eds.), Climate Change 2001: The scientific basis: Cambridge University Press, 639-693.

Clark, J.S. and others. 2001. Ecological forecasts: an emerging imperative. *Science* **293**: 657-660

Croteau, M-N, in preparation. Contrasting Cd and Cu biodynamics in freshwater snails using a metal stable isotope approach.

Cubasch, U., and Meehl, G.A., 2001, Projections of future climate change, in Houghton and others (eds.), Climate Change 2001: The scientific basis: Cambridge University Press, 525-582.

Dettinger, M.D.and Cayan, D.R., 1992, Climate-change scenarios for the Sierra Nevada, California, based on winter atmospheric-circulation pattern: Proceedings, 1992 AWRA Conf., Reno, Nev., 681-690.

Dettinger, M.D., Cayan, D.R., Meyer, M.K., and Jeton, A.E., 2004, Simulated hydrologic responses to climate variations and change in the Merced, Carson, and American River basins, Sierra Nevada, California, 1900-2099. *Climatic Change*, **62**: 283-317.

Dettinger, M.D., in press, From climate-change spaghetti to climate-change distributions for 21st Century California. *San Francisco Estuary and Watershed Science*, 21 p.

Feyrer F. and Healey M.P. 2003. Fish community structure and environmental correlates in the highly altered southern Sacramento-San Joaquin Delta. *Environmental Biology of Fishes* **66**:123-132.

Foe, D., Davis, J., Schwarzback, S., Stephenson, M., and Slotton, D. 2002. Conceptual model and working hypotheses of mercury bioaccumulation in the Bay-Delta ecosystem and its tributaries. LINK.

Foe, C. and A. Knight. 1985. The effect of phytoplankton and suspended sediment on the growth of *Corbicula fluminea* (Bivalvia). *Hydrobiologia* **127:** 105-115.

Foxgrover, A.C, Higgins, S.A., Ingraca, M.K., Jaffe, B.E. and Smith, R.E., 2004. Deposition, erosion and bathymetric change in South San Francisco Bay: 1858-1983, USGS OFR 2004-1192, 25 p. LINK.

Gleick, P.H., 1987, The development and testing of a water balance model for climate change impact assessment-Modeling the Sacramento basin: *Wat. Resour. Res.* **23:** 1049-1061.

Gross, E.S., J.R. Koseff, and S.G. Monismith. 1999. Three-dimensional salinity simulations of South San Francisco Bay. *Journal of Hydraulic Engineering* 1199-1209.

Hauenstein, E., and Ramirez, C. 1986. The influence of salinity on the distribution of Egeria densa in the Valdivia river basin, *Chili. Arch. Hydrobiol.* **107**:511-519

Hayhoe, K. and others. 2004. Emissions pathways, climate change, and impacts on California. *Proceedings of the National Academy of Sciences* **34**:12422-12427.

Hornberger, M.I., Luoma, S.N., Cain, D.J., Parchaso, F., Brown, C.L., Bouse, R.M., Wellise, C., and Thompson, J.K. 2000. Linkage of bioaccumulation and biological effects to changes in pollutant loads in South San Francisco Bay. *Environ. Sci. Technol* **34**: 2401-2409.

Jaffe, B. E., Smith, R. E., and Torresan, L. Z. 1998. Sedimentation and bathymetric change in San Pablo Bay: 1856 to 1983: U.S. Geological Survey Open-File Report 98-759.

Jaffe, B. E., Smith, R. E., and Foxgrover, A., in press, Anthropogenic Influence on Sedimentation and Intertidal Mudflat Change in San Pablo Bay, California: 1856 to 1983, *Estuarine, Coastal and Shelf Science*.

Jassby A.D., Kimmerer W.J., Minismith S.G., Armor C., Cloern J.E., Powell T.M., Schubel J.R., and Veldinsli T.J. 1995. Isohaline position as a habitat indicator for estuarine populations. *Ecol. Applications* 5:272-289.

Jassby, A. D. and J. E. Cloern. 2000. Organic matter sources and rehabilitation of the Sacramento-San Joaquin Delta (California, USA), 10 ed.

Jassby, A. D., J. E. Cloern, and B. E. Cole. 2002. Annual primary production: patterns and mechanisms of change in a nutrient-rich tidal ecosystem. *Limnol. Oceanogr.* **47:** 698-712.

Jeton, A.E., Dettinger, M.D., and Smith, J.L., 1996, Potential effects of climate change on streamflow, eastern and western slopes of the Sierra Nevada, California and Nevada: USGS WRI Report 95-4260, 44 p.

Kimmerer, W.J., 2002. Effects of freshwater flow on abundance of estuarine organisms: physical effects or trophic linkages. *Mar Ecol Prog Ser* **243**:39-55

Knowles, N., D. Cayan, L. Ingram, D. H. Peterson, and R. J. Uncles, 1997: Diagnosing the Flood of 1997 in San Francisco Bay with Observations and Model Results. *Interagency Ecological Program Newsletter*, 10.

Knowles, N., and Cayan, D., 2002, Potential effects of global warming on the Sacramento/San Joaquin watershed and the San Francisco estuary: *Geophysical Research Letters*, **29**

Knowles, N., and D. Cayan, 2004, Elevational Dependence of Projected Hydrologic Changes in the San Francisco Estuary and Watershed. *Climatic Change*, **62**: 319-336.

Leung, L.R., Qian, Y., Bian, X., Washington, W.M., Han, J., and Roads, J.O., 2004, Mid-century ensemble regional climate change scenarios for the Western United States: *Climatic Change*, **62**: 75-113.

Linville, R.G., S.N. Luoma, L. Cutter, G.A. Cutter, 2002. Increased selenium threat as a result of invasion of the exotic bivalve *Potamocorbula amurensis* into the San Francisco Bay-Delta. *Aqu. Toxic.* **57**:51-64

Lionberger, M.A., and Schoellhamer, D.H., 2003, A tidally averaged sediment transport model of San Francisco Bay, California: Proceedings of the 6th biennial State-of-the-Estuary Conference, Oakland, California, October 21-23, 2003, p. 118.

Lopez, C. B., James E. Cloern, Tara S. Schraga, Amy J. Little, Lisa V. Lucas, and Janet K. Thompson. "Ecological Values of Shallow-Water Habitats: Implications for Restoration of Disturbed Ecosystems" Submitted to *Ecosystems*.

Lucas, L. V., J. R. Koseff, J. E. Cloern, S. G. Monismith, and J. K. Thompson. 1999a. Processes governing phytoplankton blooms in estuaries. I: The local production-loss balance. *Mar. Ecol. Prog. Ser.* **187:** 1-15.

Lucas, L. V., J. R. Koseff, S. G. Monismith, J. E. Cloern, and J. K. Thompson. 1999b. Processes governing phytoplankton blooms in estuaries. II: The role of horizontal transport. *Mar. Ecol. Prog. Ser.* **187:** 17-30.

Lucas, L. V. and J. E. Cloern. 2002. Effects of tidal shallowing and deepening on phytoplankton production dynamics: A modeling study. *Estuaries* **25:** 497-507.

Lucas, L.V., Cloern, J.E., Thompson, J.K., and Monsen, N.E., 2002. Functional variability of shallow tidal habitats in the Sacramento-San Joaquin Delta: restoration implications. *Ecological Applications* v. **12**, no. **5**, p. 1, 528-1, 547. LINK.

Luoma, S.N., Cain, D.J., and Johansson, C. 1985. Temporal Fluctuations of Silver, Copper and Zinc In the Bivalve Macoma balthica at Five Stations in South San Francisco Bay. *Hydrobiologia* **129**: 102-120.

Luoma, S. N. and Presser, T. 2000. Forecasting Selenium Discharges to the San Francisco Bay-Delta Estuary: Ecological Effects of a Proposed San Luis Drain Extension. No. USGS Open-File report 00-416, LINK.

McMahon, R.F. 1999. Invasive characteristics of the freshwater bivalve *Corbicula fluminea. In.* Nonindigenous Freshwater Organisms. R.Claudi and J.H. Leach (Eds.), Lewis Publishers, New York, NY

315-343.

Monsen, N.E. 2001. A study of sub-tidal transport in Suisun Bay and the Sacramento-San Joaquin Delta, California. PhD thesis. Stanford University.

Moyle, P. B. 2002. Inland Fishes of California. University of California Press, Berkeley, California.

Mueller-Solger, A. B., A. D. Jassby, and C. D. Mueller-Navarra, 2003. Nutritional quality of food resources for zooplankton (Daphnia) in a tidal freshwater system (sacramento-san joaquin river delta). *Limnol. Oceanogr.* **45:** 1468-1476.

Parchaso. F., and J. Thompson. 2002. Influence of hydrologic processes on reproduction of the introduced bivalve *Potamocorbula amurensis* in Northern San Francisco Bay, California. *Pacific Science* **56**:329-345

Parchaso, F., J. Thompson, 2004. Distribution And Grazing Potential Of *Corbicula Fluminea*. In The Sacramento-San Joaquin Delta Proceedings of the 2004 CALFED Bay-Delta Program Science Conference.

Puccia C.J. and Levins R. 1985. Qualitative Modelling of Complex Systems. An Introduction to Loop Analysis and Time Averaging. Harvard University Press, Cambridge, MA.

Roelvink, J.A., Jeuken, M.C.J.L., van Holland, G., Aarninkhof, S.G.L. and Stam, J.M.T., 2001. Long-term, process-based modeling of complex areas. Proc. 4th Coastal Dynamics Conference, Lund, Sweden, 383-392

Rosati, A. and K. Miyakoda. 1988. A general circulation model for upper ocean simulation. *Journal of Physical Oceanography* **18(11):** 1601-1626.

Ruth, M. and Lindholm, J. 2001. Dynamic Modeling for Marine Conservation. Springer Pub. NY, NY. 449 pp

Schlekat, C.E., Lee, B.G., and Luoma, S.N. 2001. Dietary metals exposure and toxicity to aquatic organisms: Implications for ecological risk assessment. In Coastal and estuarine risk assessment. Edited by M.C.Newman, M.H.Roberts, and R.C.Hale. CRC Press, Boca Raton pp. 151-188.

Schwartz, P. 1991. The Art of the Long View: Planning for the Future in an Uncertain World. Currency Doubleday. 272 p.

Sobczak, W. V., J. E. Cloern, A. D. Jassby, and A. B. Mueller-Solger. 2002. Bioavailability of organic matter in a highly disturbed estuary: the role of detrital and algal resources. *PNAS* **99:** 8101-8105.

Sommer, T., M. L. Nobriga, W. C. Harrell, W. Batham, and W. Kimmerer. 2001. Floodplain rearing of juvenile chinook salmon: evidence of enhanced growth and survival. *Canadian Journal of Fisheries and Aquatic Sciences* **58**:325–333

Stewart, A.R., Luoma, S.N., Schlekat, C.E., Doblin, M.A. and Hieb, KA., 2004. Food Web Pathway Determines How Selenium Affects Aquatic Ecosystems: A San Francisco Bay Case Study. *Environ. Sci. Technol.* **38(17)**:4519-4526. LINK.

Tarboton, D.G., 1995, Hydrologic scenarios for severe sustained drought in the Southwestern United States: *Water Resources Bulletin*, **3:** 803-813.

Tarboton, D. G., and C. H. Luce, 1996: Utah Energy Balance Snow Accumulation and Melt Model (UEB): Computer model technical description and users guide.

Thompson, J.K., 2004. One estuary, one invasion, two responses: phytoplankton and benthic community dynamics determine the effect of an estuarine invasive suspension feeder. In: The comparative Roles of Suspension Feeders in Ecosystems, S. Olenin and R. Dame Editors. In Press.

Uncles, R. J., and D. H. Peterson, 1995: A Computer Model of Long-Term Salinity in San Francisco Bay - Sensitivity to Mixing and Inflows. *Environment International,* **21**: 647-656.

Walther, G.-R. and others. 2002. Ecological responses to recent climate change. *Nature* **416**: 389-395.

Warner, J.C., Schoellhamer, D.H., Ruhl, C.A., and Burau, J.R., 2004, Floodtide pulses after low tides in shallow subembayments adjacent to deep channels: *Estuarine, Coastal and Shelf Science,* v. **60**, no. **2**, p. 213-228.

Wei, L.P. and Guan, RT. 1986. Growing and breeding habits of *Potamocorbula laevis*. *Trans. Chin Soc. Malacol.* **2**:94-101

Wilby, R.L., and Dettinger, M.D., 2000, Streamflow changes in the Sierra Nevada, California, simulated using statistically downscaled general circulation model output, in S. McLaren and D. Kniveton (eds.), Linking Climate Change to Land Surface Change: Advances in Global Change Research, 6, Kluwer Academic Publishers, 99-121.

Winterwerp, J.C., 2001. Stratification effects by cohesive and non-cohesive sediment, *Journal of Geophysical Res.*, Vol. 106, No. C10, pp 22,559-22,574, October 15, 2001.

Wright, S.A., and Schoellhamer, D.H., 2004, Suspended sediment transport where rivers become estuaries: Sacramento – San Joaquin River Delta, water years 1999-2002: Proceedings of the 2004 CALFED Science Conference, Sacramento, California, October 4-6, 2004, p. 237. LINK.

Wright, S.A., and Schoellhamer, D.H., submitted, Suspended sediment transport where rivers become estuaries: Sacramento – San Joaquin River Delta, water years 1999-2002: *Water Resources Research*.

5. Figures
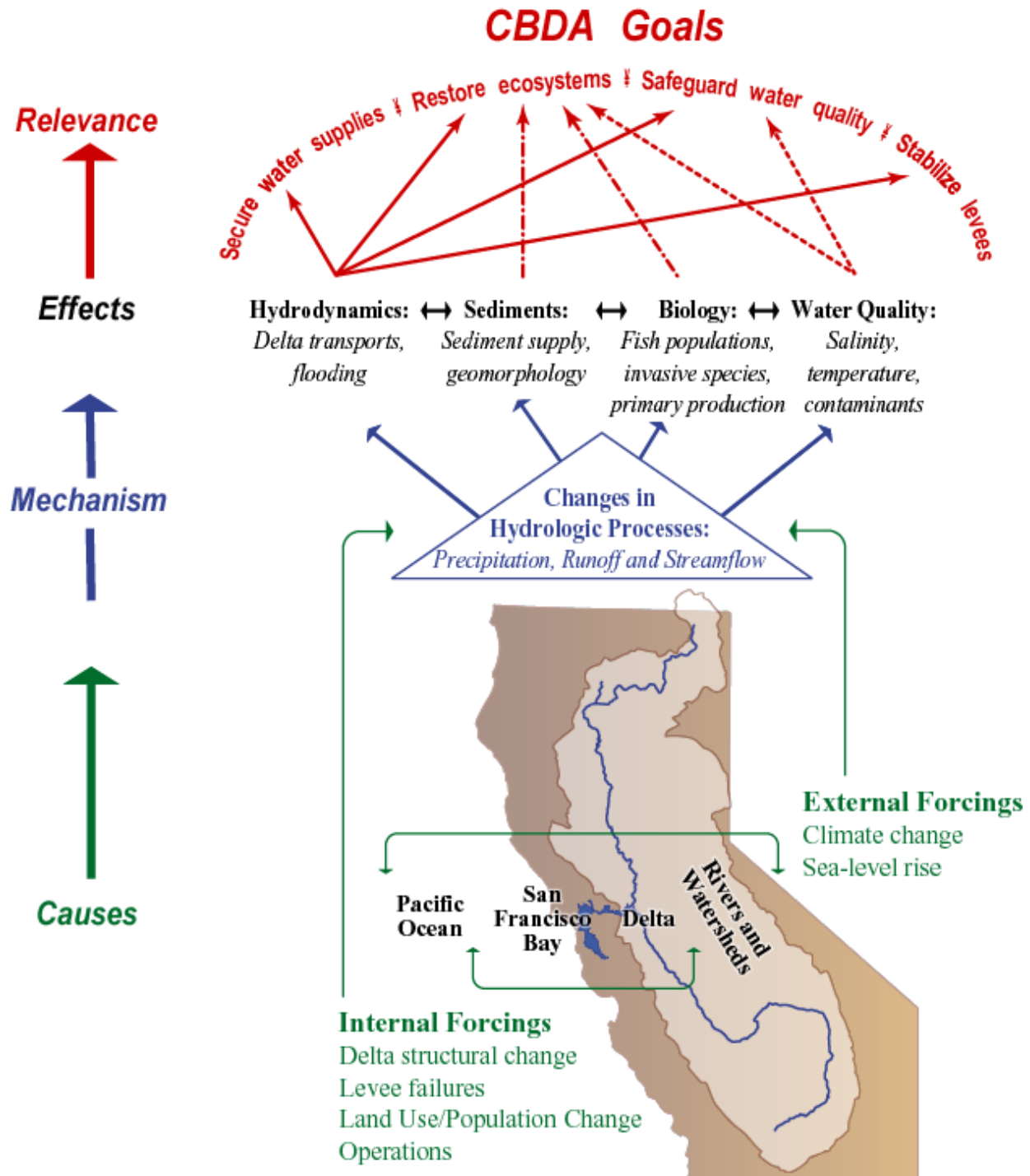
Figure 1. Conceptual model of external and internal forcings as drivers of change in hydrologic processes within the BDRW system, and of hydrologic change as the mechanism of cascading responses that include altered hydrodynamics and transports, sediment supplies and evolving geomorphology of the Bay and Delta, distributions of salinity and seasonal water temperature, loadings and bioaccumulation of toxic contaminants, and population responses of alien and native species including native fishes targeted for rehabilitation. The indicated connections between these complex cause-effect relationships and the four general goals of CBDA agencies will be addressed in this study.
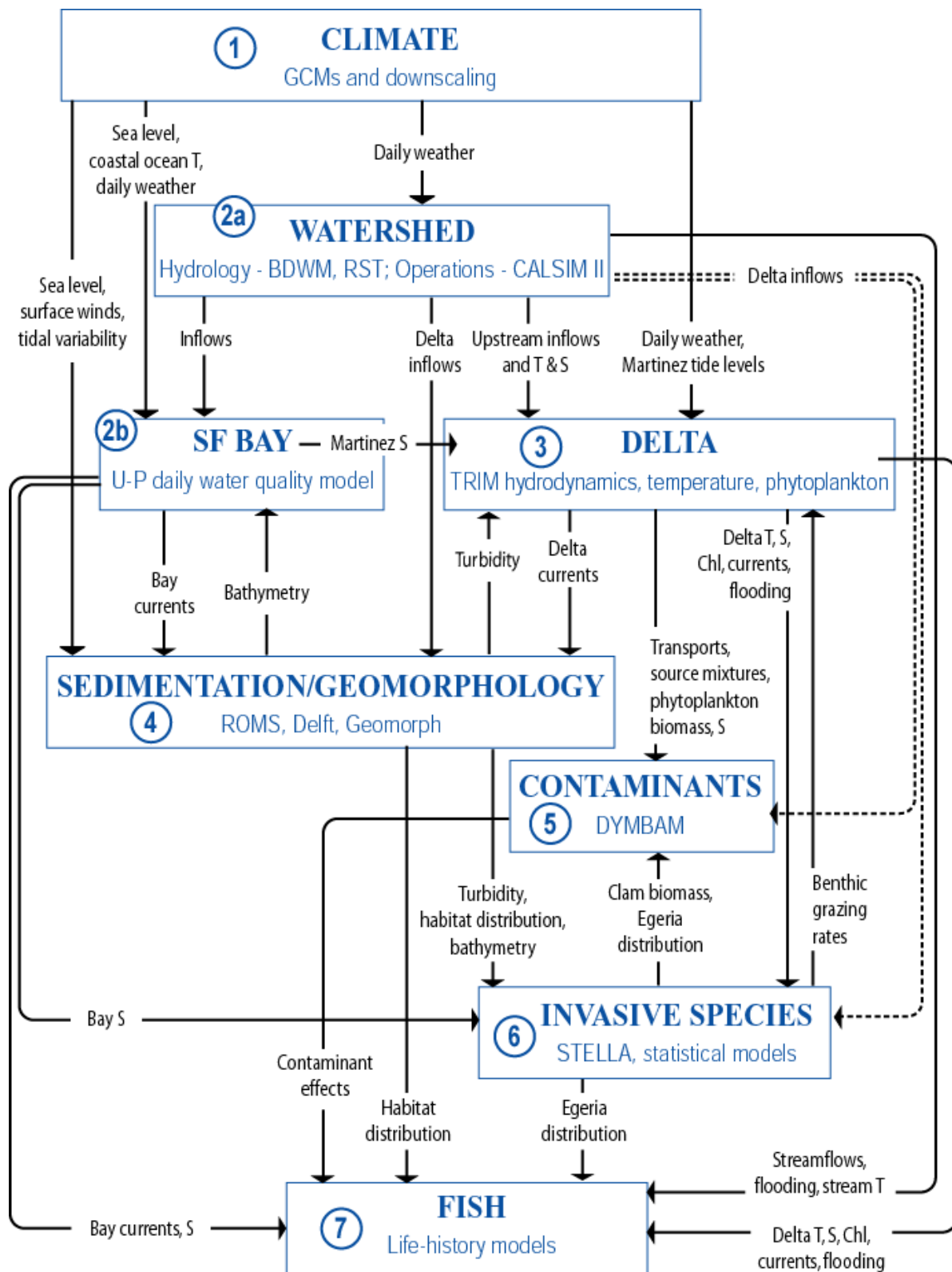
Figure 2. Data flow between project elements. To begin, scenarios of future climate will be produced by the climate element①; projected patterns of future land use and freshwater demand will be used to configure the hydrologic and operations models in ②**a**; and scenarios of Delta configuration change will be used to configure the models used in ③ and ④. Then, under a given scenario, each project element will use the indicated modeling approaches to provide data to other project elements, including, salinity (S), temperature (T), and chlorophyll (Chl). Cumulative model outputs will be synthesized into assessments of habitat quality change and potential population responses of native and alien species within the Delta.
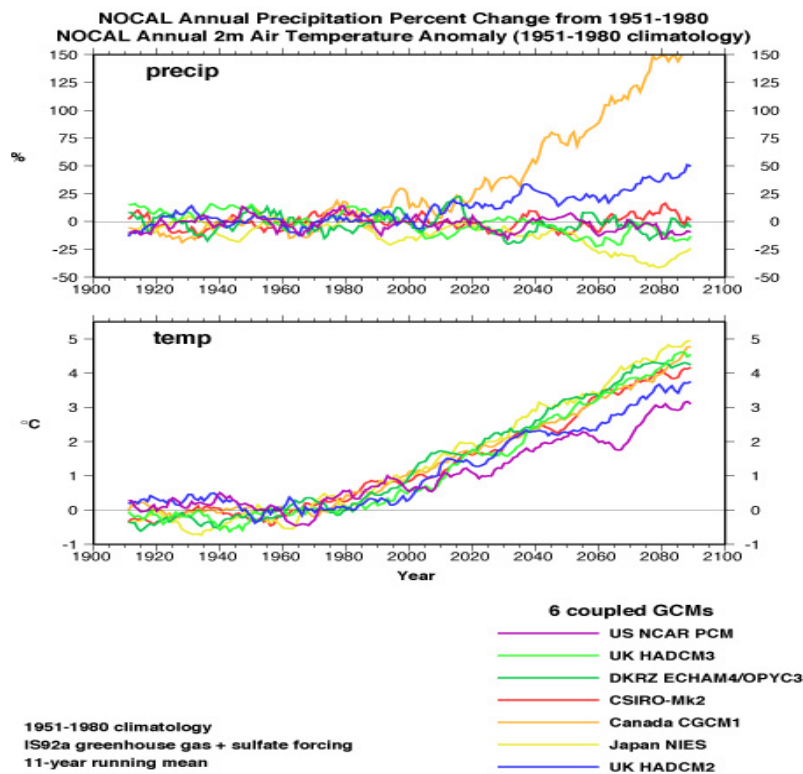
Figure 3. Comparisons of projected annual-mean changes in **top**: precipitation and **bottom:** surface-air temperatures over northern California in coupled global ocean-atmosphere climate models under estimated-historical and standard "business-as-usual" greenhouse-gas plus sulfate-aerosol emission scenarios for the 20th and 21st Centuries.
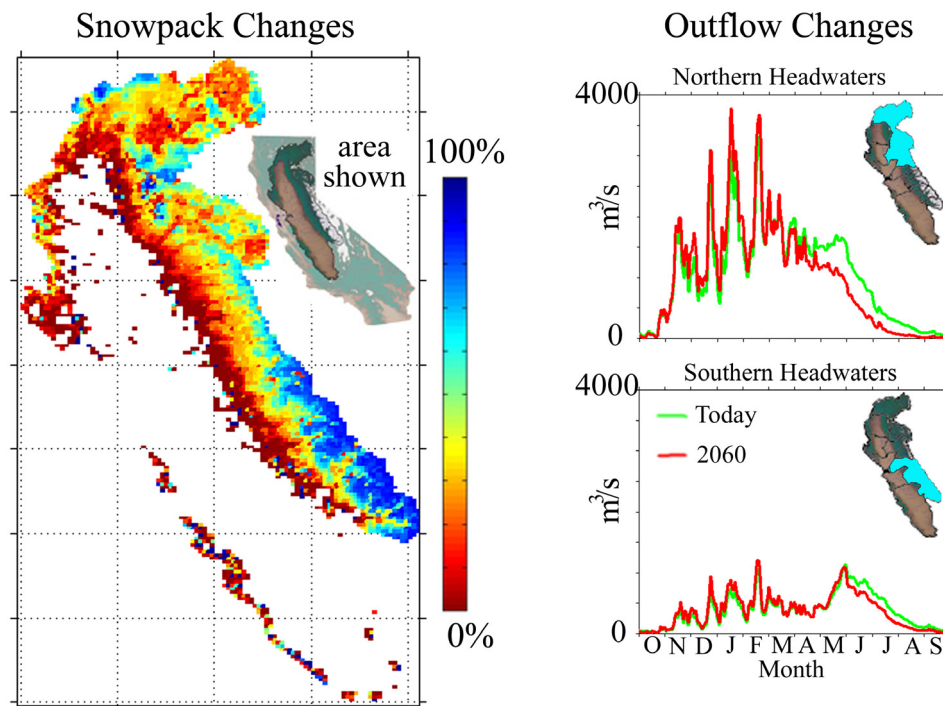
Figure 4. Projected remaining snowpack by 2060 (**left**) expressed as a percentage of present-day levels, and resulting changes in mean annual cycles of regional runoff (**right**). This is an application of the BDWM in which climate change projections were used to drive the model to assess potential hydrologic impacts by the year 2060. While the watershed's total snowpack volume is projected to diminish by one-third, most of this loss is focused in the moderate elevations of the northern Sierra and Cascade ranges, resulting in larger annual runoff changes in the North (Knowles and Cayan 2002).

Future Delta Configuration

2) North Delta Flood Control and
Ecosystem Improvement Program
a) flood McCormack-Williamson tract
configuration TBD
b) South Fork Mokelumne: levee setbacks
c) dredging/levee setbacks in Georgiana Sl.
and North Fork Mokelumne TBD when
further information is available

1) South Delta Improvements Project
a) dredge Delta channels
b) operable barriers
c) entrance to Clifton Court Forebay
and intertie configuration TBD when
when further information is available

3) Lower San Joaquin Flood
Improvements
a) dredge lower San Joaquin
b) dredge portions of Old
and Middle Rivers

Figure 5. The scenario of change in the Delta's physical configuration, taken from the California Bay-Delta Program Conveyance Program Multi-Year Program Plan Years 5-8 (calwater.ca.gov/ProgramPlans_2004/Conveyance_ Program_Plan_7-04.pdf). Three major projects will be included: a) South Delta Improvements Proje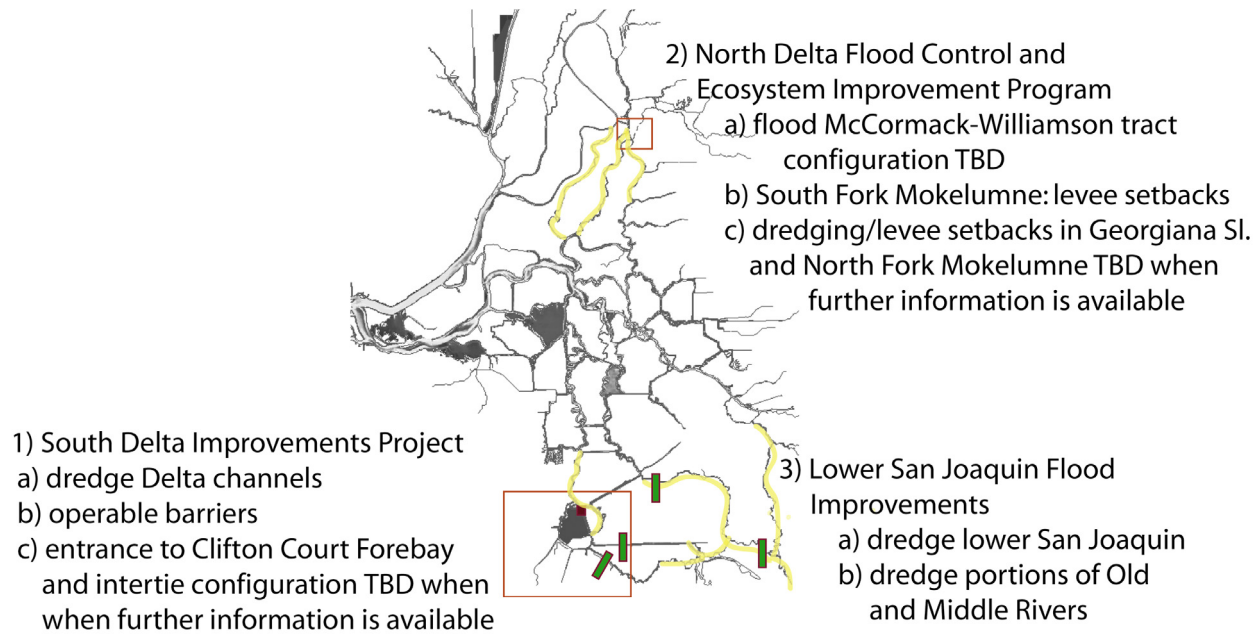ct, b) North Delta Flood Control and Ecosystem Improvement Program, and c) Lower San Joaquin River Flood Improvements. This configuration includes an intertie channel between the state (SWP) and federal (CVP) pumps, flooding of McCormack-Williamson tract, installation of south Delta barriers, and channel widening (or levee setbacks) on the Mokelumne, Georgiana Slough, San Joaquin R., Middle R., and Old R. Delta TRIM will be modified to represent this configuration. This suggested configuration might be altered based on additional information from the Delta Improvements Package Plan and the Delta Regional Ecosystem Restoration Implementation Plan (delta.dfg.ca.gov/erpdeltaplan/), once these documents are available in their final form.

2) Two breaks on Webb Tract
(~2.5 m deep)

1) Break on San Joaquin
at Sherman Island (~2.5 m deep)

3) Break on Woodward Island
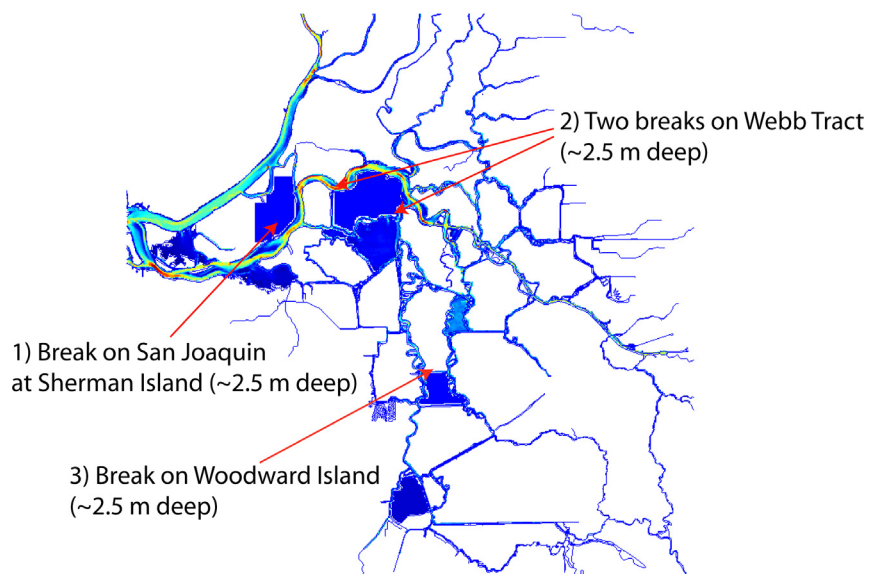(~2.5 m deep)

Figure 6. The scenario of catastrophic levee failure in the Delta, prescribed as flooding (to a depth of ~2.5 m) in Sherman Island, Webb Tract and Woodward Island. This scenario is based on levees recently repaired (Kurosaka talk 2/6/2004) and the CALFED Levee System Integrity Program Plan (calwater.ca.gov/Programs/ LeveeSystemIntegrity/LeveeSystemProgramPlan.shtml)
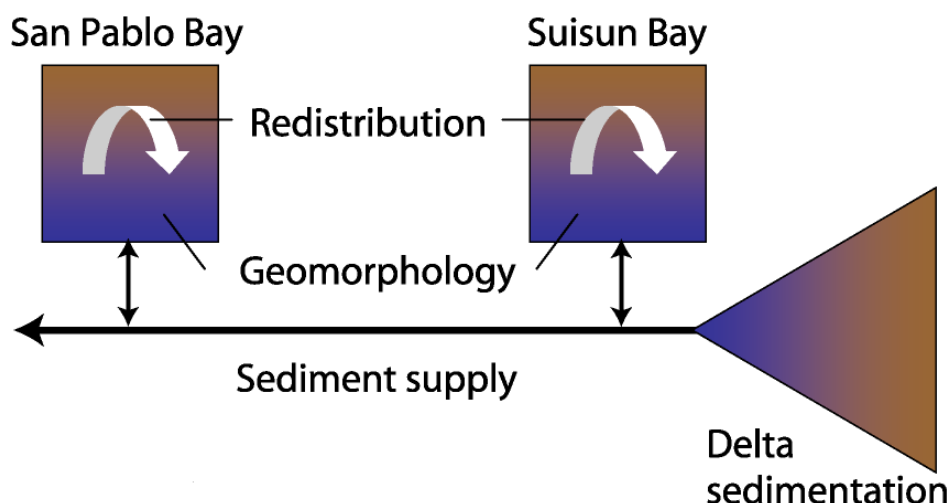
Figure 7. Linked models of geomorphic evolution. Delta sedimentation model will extrapolate recently collected sediment load data; and route suspended sediment load through main conduits. Sedimentation within Delta channels will be estimated, and export from the Delta is routed to the Bay. Sediment supply from the Delta will be delivered to Suisun Bay using available 1-D, 2-D and 3-D models, followed by redistribution modeling within Suisun Bay. The subsequent export to San Pablo Bay can then be distributed within San Pablo Bay using 3-D modeling techniques, followed by the ultimate export of sediment out of the Bay/Delta system. Net geomorphic change in each subembayment will be the final result, estimating the distribution of diverse habitat (i.e. channel, mudflat, marsh).

Figure 8. Pollutant effects in San Francisco Bay are tied in complex and interactive ways to hydrology, hydrodynamics, sediment transport, ecological processes and food web structure (e.g. Brown *et al.* 2003; Luoma *et al.* 1985; Luoma and Presser 2000; Stewart *et al.* 2004). The approach outlined above will be extended to include other contaminants as described in ⑤.

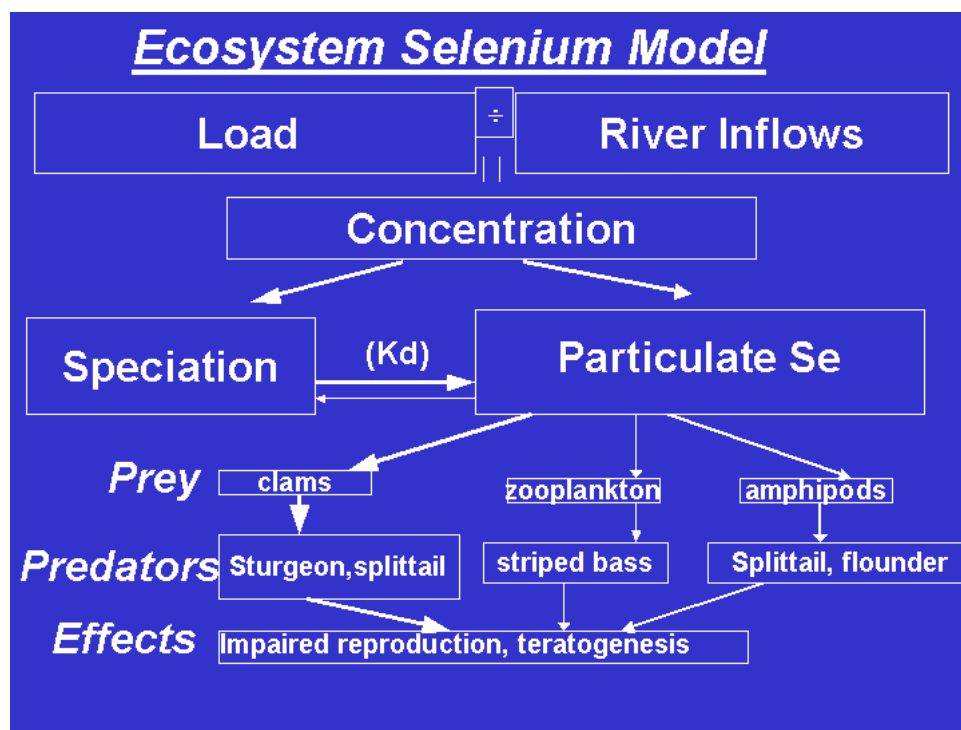| Parameter	Dependencies	Literature Citation or Data Source
Egeria densa		
Salinity limit	<5 psu maintenance <8psu survival	Hauenstein & Ramirez 1986
Temperature limit	28˚ C limits; <16 & >32˚ C poor growth	Barko &Smart 1981
Depth limit	<3.5 m	Romberg Tiburon Web, personal observation
Velocity limit	<1 m/s	Chambers et al 1991
Corbicula fluminea		
Growth Rate	Function of temperature/food	Foe and Knight 1985, Foe et al. 2002
Mortality Rate	TBD (1977-2003)	DWR
Fecundity	Function of weight/food	McMahon 1999
Recruitment	TBD (1977-2003)	DWR
Immigration	TBD (1977-2003)	DWR, USGS (2002 only)
Distribution	Salinity, temperature, velocity, substrate	McMahon 1999
Potamocorbula amurensis		
Growth Rate	TBD (1988-2003)	USGS, DWR, Thompson 2004
Mortality Rate	TBD (1988-2003)	USGS, DWR, Thompson 2004
Fecundity	Function of size/weight	From congener; Wei and Guan 1986
Recruitment	TBD (1988-2003)	USGS, DWR, Parchaso & Thompson 2002, Nicolini & Penry 2000
Immigration	TBD (1988-2003)	USGS, DWR
Distribution	Salinity, temperature, substrate	USGS, DWR, Clark et al. 2000

Figure 9. Source for life history parameters for Egeria, Corbicula, and Potamocorbula to be used in statistical and STELLA models. (*TBD to be determined from field data during study with data years in parentheses)
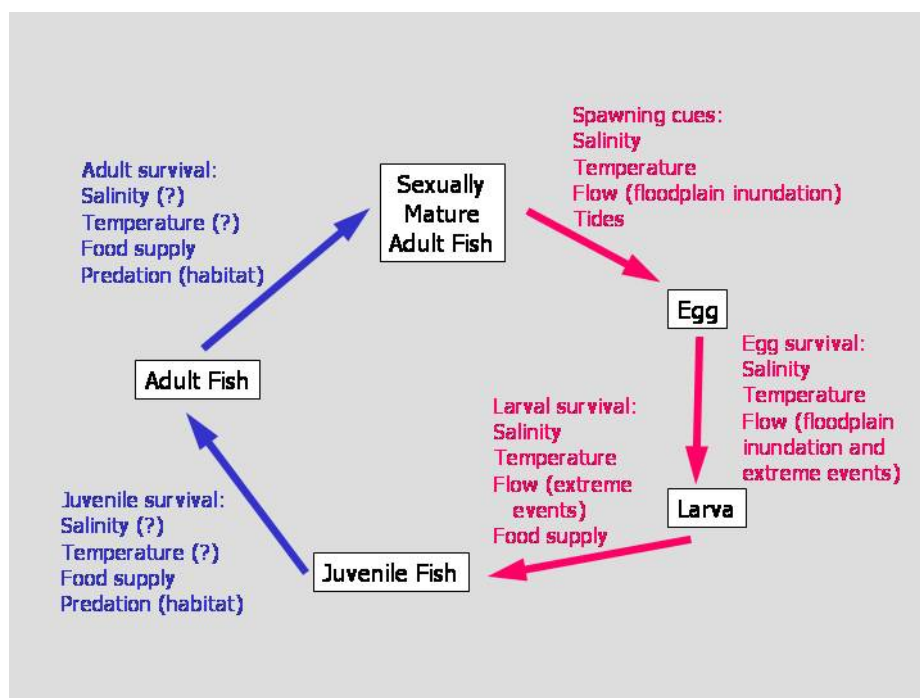

Figure 10. A hypothetical example of a life-cycle model for a fish species of interest. In this example, environmental effects are assumed to be most critical from adult spawning to juvenile recruitment (red). Juvenile and adult stages (blue) are usually more tolerant of environmental extremes and are more mobile, allowing them to move out of unfavorable areas.
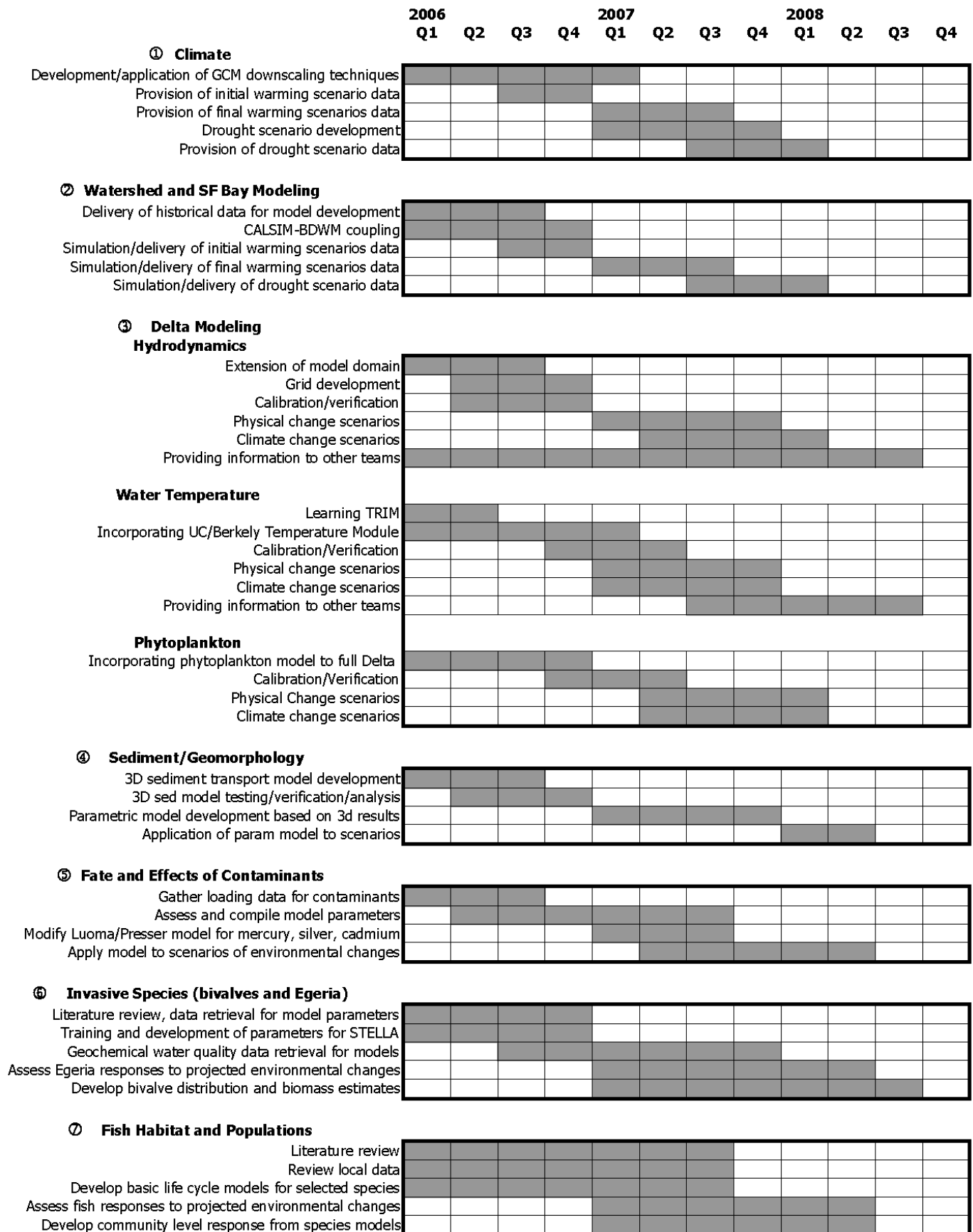
2006 Q1 Q2 Q3 Q4 **2007** Q1 Q2 Q3 Q4 **2008** Q1 Q2 Q3 Q4

① **Climate**
Development/application of GCM downscaling techniques
Provision of initial warming scenario data
Provision of final warming scenarios data
Drought scenario development
Provision of drought scenario data

② **Watershed and SF Bay Modeling**
Delivery of historical data for model development
CALSIM-BDWM coupling
Simulation/delivery of initial warming scenarios data
Simulation/delivery of final warming scenarios data
Simulation/delivery of drought scenario data

③ **Delta Modeling**
Hydrodynamics
Extension of model domain
Grid development
Calibration/verification
Physical change scenarios
Climate change scenarios
Providing information to other teams

Water Temperature
Learning TRIM
Incorporating UC/Berkely Temperature Module
Calibration/Verification
Physical change scenarios
Climate change scenarios
Providing information to other teams

Phytoplankton
Incorporating phytoplankton model to full Delta
Calibration/Verification
Physical Change scenarios
Climate change scenarios

④ **Sediment/Geomorphology**
3D sediment transport model development
3D sed model testing/verification/analysis
Parametric model development based on 3d results
Application of param model to scenarios

⑤ **Fate and Effects of Contaminants**
Gather loading data for contaminants
Assess and compile model parameters
Modify Luoma/Presser model for mercury, silver, cadmium
Apply model to scenarios of environmental changes

⑥ **Invasive Species (bivalves and Egeria)**
Literature review, data retrieval for model parameters
Training and development of parameters for STELLA
Geochemical water quality data retrieval for models
Assess Egeria responses to projected environmental changes
Develop bivalve distribution and biomass estimates

⑦ **Fish Habitat and Populations**
Literature review
Review local data
Develop basic life cycle models for selected species
Assess fish responses to projected environmental changes
Develop community level response from species models

Figure 11. Timelines showing the progression of tasks for each element of a three-year research project to assess responses of the Bay-Delta-River-Watershed system to scenarios of 21st century change. All elements will perform analysis and reporting (not shown) during the project's 3rd year.